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ANALYSIS OF BANK STABILITY IN THE DEC WATERSHEDS, MISSISSIPPI

Final Technical Report

by

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Many bluff-line streams in Mississippi are experiencing serious instability as a result of channel degradation. Degradation lowers the bed of the channel, leading to undermining of bridges and other structures and the generation of heavy sediment loads that cause aggradation problems further downstream in the systems. Bed lowering also increases bank heights and angles, reducing bank stability with respect to mass failure under gravity. Eventually, as the bed lowers, the banks become unstable and collapse. The critical height and the mechanism of failure are functions of the bank geometry and the engineering properties of the bank materials. When the banks attain the critical height for mass failure a major geomorphic threshold is crossed and the thrust of channel instability switches from degradation to rapid widening. (TURN OVER)

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In this report bank stability analyses recently developed by Osman and Thorne are used to develop generalized bank stability charts that may be used to predict critical bank height.

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ABSTRACT

Many bluff-line streams in Mississippi are experiencing serious instability as a result of channel degradation. Degradation lowers the bed of the channel, leading to undermining of bridges and other structures and the generation of heavy sediment loads that cause aggradation problems further downstream in the systems. Bed lowering also increases bank heights and angles, reducing bank stability with respect to mass failure under gravity. Eventually, as the bed lowers, the banks become unstable and collapse. The critical height and the mechanism of failure are functions of the bank geometry and the engineering properties of the bank materials. When the banks attain the critical height for mass failure a major geomorphic threshold is crossed and the thrust of channel instability switches from degradation to rapid widening.

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In this report bank stability analyses recently developed by Osman and Thorne are used to develop generalized bank stability charts that may be used to predict critical bank height.

KEYWORDS

Alluvial channels, Bank erosion, Channel stability,

Demonstration Erosion Control Project, Degradation,

Mississippi, River mechanics, River modeling,

Riverbank erosion, Riverbank failure, Sedimentation

Streams

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CONVERSION FACTORS

To convert	To	Multiply by
feet (ft)	meters (m)	0.3048
miles (mls)	kilometers (km)	1.6093
square feet (ft^2)	square meters (m^2)	0.0929
square miles (sq mls)	square kilometers (km^2)	2.5899
acres (acre)	hectares (ha)	0.4046
cubic feet (ft^3)	cubic meters (m^3)	0.0283
cubic feet per sec. (ft^3/s)	cumecs (m^3/s)	0.0283
pounds force (lb)	newtons (N)	4.4482
pounds per sq. foot (psf)	kilopascals (kPa)	0.0478
pounds per cu. foot (pcf)	kilonewtons/cu meter (kN/m^3)	0.1571

NOTATION

BW	block width
c'	effective cohesion
DW	lateral erosion distance
DZ	bed degradation distance
FS	factor of safety for initial failure
FSS	factor of safety for subsequent failures
H	total bank height
H'	height of sloping bank (above zone of toe erosion)
H_o	bank height prior to degradation
i	bank angle
K	ratio of tension crack depth to total bank height
N_g	channel stability number for geotechnical stability (from WET, 1987)
N_s	stability number
VB	volume of failure block per unit channel length
Wt	Block weight
Y	depth of tension crack
	specific weight of bank material
	effective friction angle
	failure plane angle
crit	subscript indicating value at failure

I INTRODUCTION

Many of the streams that drain the bluff-line in Mississippi have degraded seriously in the last fifty years. It is difficult to be precise concerning the cause of this degradation, because the streams have been subjected to a wide variety of changes in the parameters controlling bed stability. Some have been imposed by mankind, but others are entirely natural in origin. Indeed there is evidence in the stratigraphic record in the flood plain sediments deposited by the bluff-line streams that cycles of degradation followed by massive aggradation were occurring long before the area was settled by man (Grissinger et al. 1982). In separate studies by Patrick et al. (1982), Schumm et al. (1984), and Harvey and Watson (1986), however, the current degradation driven instability has been attributed to:-

1. Reduced sediment supply from the watersheds to the streams due to changes in land-use and improved soil conservation methods;

2. Increased sediment transport capacity due to channel straightening and snagging for increased flood protection;

3. Bed scouring due to the lowering of effective base level through trunk stream regulation by flood control reservoirs.

Degradation primarily occurs by the upstream migration of a knick point. The streams lack geologic controls formed from bed rock outcrops, but in places the channel bed is formed in erosion resistant clays or cemented iron stone. At these locations the knick point may form a headcut with an overfall between 2 and 6 feet high when the resistant layer is breached. Usually, however, the knick point is not so clearly defined. It occurs as an over-steepened reach that may be identified by a trained eye in the field, or is readily discernible as an upward convexity in a plot of the long-profile. Upstream of the knick point the channels appear to be in good condition. The banks are well vegetated with a variety of tree species including willow, birch and sycamore, indicating that the banks have been stable for a period of at least several decades. The beds show reasonable but not excessive accumulations of sediment, usually arranged in an orderly fashion as alternate bars or point bars, suggesting that neither aggradational or degradational trends are prevalent. In line with these qualitative observations, the channels conform to regime type relations developed for stable channels. However, downstream of the knick point the streams lose this coherent hydraulic geometry. Their channels are heavily incised and have a ragged appearance, with little or no bed sediment accumulations.

Degradation causes serious problems through spreading instability throughout the fluvial systems in the bluff-line

streams. Progressive lowering of the bed through degradation necessitates costly repair work at hydraulic structures and bridges, destroys the benthic layer, with negative environmental impacts, and de-waters riparian zones, often with undesirable effects on stream side vegetation and flood plain crops. The flood capacity of the degraded reaches is increased, which is a benefit, but this is offset by the large sediment output which clogs downstream channels, reducing their flood capacity and generating further instability in the system.

II STATEMENT OF PROBLEM

Although the main fluvial process in the over-steepened reaches is bed degradation, the channel banks are also seriously affected. Scour of the bed and bank toe increases the bank height and angle, both of which decrease the stability with respect to mass failure. Over-heightening and over-steepening of the banks continues until a state of limiting stability is reached and mass failure is imminent. The mechanism of failure at that time depends on the size and geometry of the bank and the engineering properties of the bank materials. The banks close to a headcut or in an over-steepened reach are relatively low, but are usually very steep and fail by a slab-type mechanism, where a column of soil partly detached from the bank by a tension crack, topples forward into the channel (Fig. 1). Further downstream bank heights are greater and angles are flatter. As a result rotational slip failures are more common than slab-type failures (fig. 2).

Failure usually occurs during "worst case" conditions when the strength of the bank materials is minimized and their weight is maximized. Such conditions are associated with periods of prolonged rainfall, snowmelt, and drawdown in the channel following a high flow stage. Hence, failure often occurs after rather than during a high flow event in the channel.

After failure the bank is stable in its new configuration, and it remains so until the basal accumulation of failed material is removed by the flow and the bank is again eroded to a limiting condition. It then fails again, the type of failure depending on the bank geometry. Hence the frequency of failures and the time-averaged rate of bank bank retreat are determined by the degree of fluvial activity at the bank base, even though the mechanism and timing of failure are not directly related to flow processes.

The onset of bank instability marks the crossing of an important intrinsic, geomorphic threshold in the response of the streams. The thrust of channel instability switches from degradation to widening. In the bluff-line streams the banks are formed in alluvially re-worked loess. The bank materials are structured silts and clays which are somewhat resistant to flow erosion in their intact, undisturbed state, but which are easily eroded once disturbed and disaggragated in a bank failure. When entrained in the flow the bank sediments disintegrate to a fine wash load, for which the streams have almost unlimited transport capacity. Consequently, once bank instability is initiated, the products of bank failures are quickly evacuated by the flow so that the banks are soon robbed of any basal protection and are left open to further over-steepening. The result is that widening progresses rapidly once the critical bank height for mass failures has been exceeded, and width increases of 200 to 300 per cent within a few months of the passage of a knick point through a reach are not uncommon.

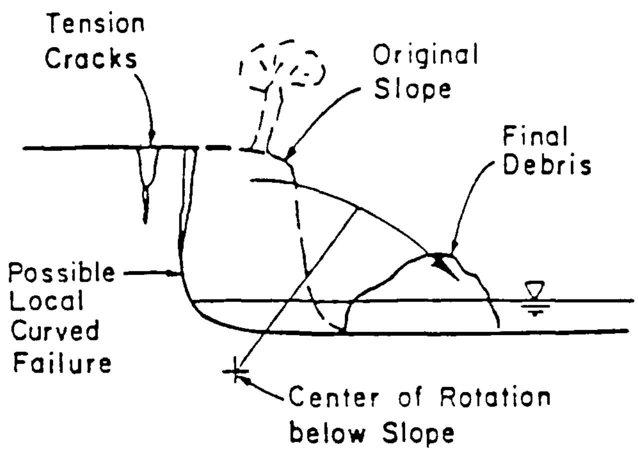

Figure 1. Slab-type failure of a steep, eroding riverbank

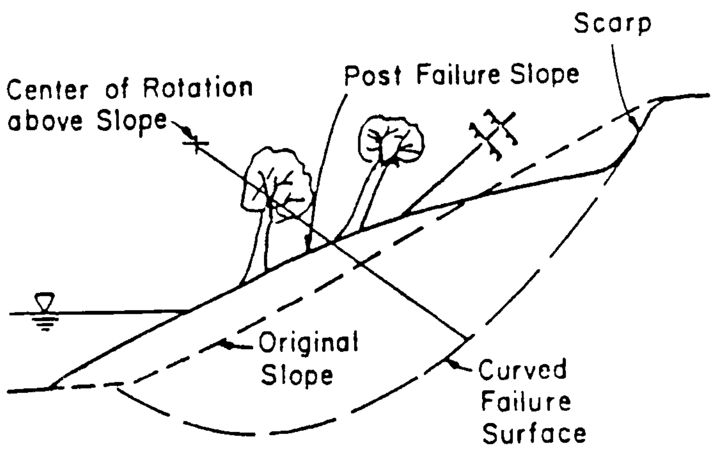

Figure 2. Rotational slip of a less steep, eroding riverbank

The possibility for degradation in the bluff-line streams to produce significant widening through initiating mass instability of the channel banks was recognized as early as 1979 in studies undertaken at the US Department of Agriculture, Sedimentation Laboratory, at Oxford, Mississippi as part of the Section 32 Streambank Erosion Demonstration Control Act (Thorne et al.,1981; Little et al., 1982). A practical method of predicting the critical bank height for failure of a bank of known slope and engineering properties was developed and tested using data from surveys of some bluff-line streams. Subsequently, the bank stability analysis has been successfully integrated into several different models for the evolution of degradational streams towards a new equilibrium (Alonso and Combs, 1986; Grissinger and Little, 1986; Harvey and Watson, 1986; Harvey et al., 1986; Simon and Hupp, 1986; Watson et al., 1986; Water Engineering & Technology, 1987).

In research at Colorado State University by Mohamed Osman (Osman,1985; Osman and Thorne, 1988), the bank stability analysis developed and applied at the USDA Sedimentation Laboratory (Thorne et al., 1981) was extensively updated and improved. Osman (Osman, 1985; Thorne and Osman, 1988) then evaluated the model using hypothetical data, and showed that it had great potential for use in analyzing and explaining the evolution of degrading streams. It was proposed in 1986 that the new model be applied to some of the bluff-line streams being studied by a Task Force of the Vicksburg District, US Army Corps of Engineers, the Mississippi Soil Conservation Service and the US Department of Agriculture, Agricultural Research Service, as part of the Demonstration Erosion Control Project (DEC). This report presents the findings of the application of the Osman-Thorne bank stability analysis in the DEC Watersheds.

In the original proposal, 5 specific tasks were identified and the body of this report is divided into 5 sections dealing with each task in turn.

III TECHNICAL REPORT

1. RIVERBANK STABILITY ANALYSIS

1.1 Theory

The analyses of slab-type and rotational slip failures of eroding riverbanks developed by Osman and Thorne are reported in detail in Osman's Ph.D thesis at Colorado State University (Osman, 1985). That for slab failure of steep banks may also be found in a recently published paper (Osman and Thorne, 1988). Only a brief outline of the analyses is included here for completeness, and those interested in examining the analysis in detail should refer to the relevant publications.

Riverbank retreat usually occurs by a combination of flow erosion and mass failure. Erosion occurs when the local fluid shear stress on the bank exceeds the shear resistance of the bank material. Failure occurs when erosion of the bank and bed adjacent to the bank increase the height and angle of the bank so that it reaches a condition of limiting stability. Close to a knick point the banks of degrading channels are usually very steep, and they commonly fail by a slab-type mechanism, where a block of soil topples forward into the channel. In this context, steep banks are defined as those with an overall bank angle greater than 60 degrees to the horizontal.

1.1.1 Slab Failure:- The analysis uses the resolution of driving and resisting forces in static equilibrium on the most critical potential failure plane to derive a factor of safety for the bank with respect to slab failure. Initially, the bank has the simple geometry shown in Fig.3a. Erosion and bed degradation operate to bring it to the critical condition with the characteristic geometry shown in Fig.3b.

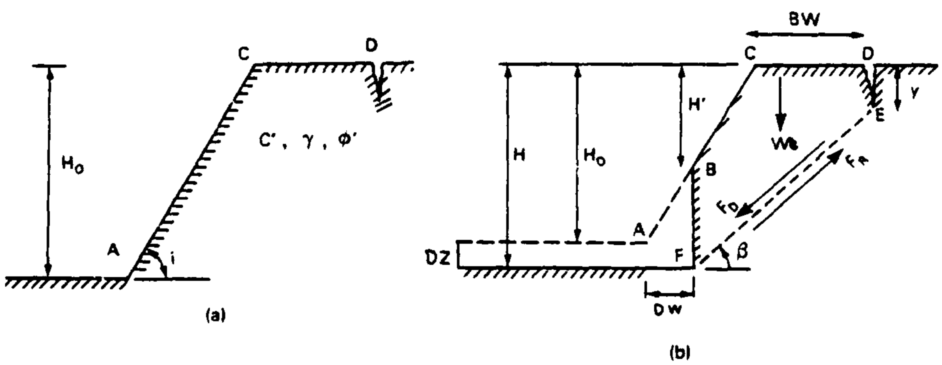

Figure 3. Analysis of initial slab-failure: a) Initial geometry; b) After erosion & degradation to a critical condition

Following the initial slab failure, the bank is stable in its new configuration (Fig. 4a). Failed material in a disturbed state comes to rest at the foot of the bank and it remains there until it is removed by the flow in the channel. This is the basal clean-out phase of bank retreat. After removal of the disturbed bank material, the flow again attacks the intact bank material, and lateral erosion recommences. Field observations support the contention that further degradation of the bed is limited once the critical bank height for mass instability is reached. Further bank failures are due mostly to lateral erosion and oversteepening of the already over-heightened banks. Consequently, the bank angle may be approximated by the failure

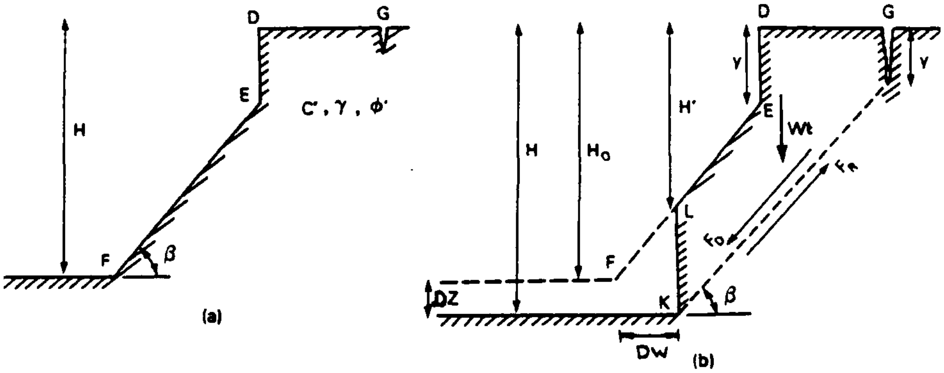

Figure 4. Analysis of subsequent slab failures: a) Geometry following initial failure and basal clean-out; b) After erosion and bed degradation to the critical condition

plane angle from the initial failure, and the bank retreats by parallel retreat when lateral erosion reduces the height of the sloping upper bank to the critical value for slab failure (Fig. 4b).

The analysis may be used to calculate the factor of safety (FS) for the initial, stable bank, and for the bank following the initial failure (FSS). Its output consists of: the amounts of bed degradation (DZ_{crit}) and/or lateral erosion (DW_{crit}) which would cause the bank to fail (These parameters are measures of the vulnerability of the bank to retreat by mass failure); Critical values of the bank height (H_{crit}); sloping bank height (H'_{crit}), tension crack depth (Y_{crit}); bank angle (i_{crit}); failure plane angle (Beta); block width (BW); and block volume per unit channel length (VB); for initial and subsequent slab failures. These parameters define the critical and post-failure

bank geometries, the amount of bank retreat, and the volume of slumped material input to the channel by each failure.

1.1.2 Rotational Slip:- Riverbanks with slope angles less than 60 degrees commonly slide along a curved failure surface that can be approximated by a circular arc passing through the toe (Fig. 5). Determination of the factor of safety for such banks depends on locating the center of rotation of the most critical potential failure arc. This requires a trial and error procedure based on the bank geometry and the soil properties. There are many approaches to the determination of the factor of safety and these were reviewed in detail by Osman (1985). Siegel (1975) developed

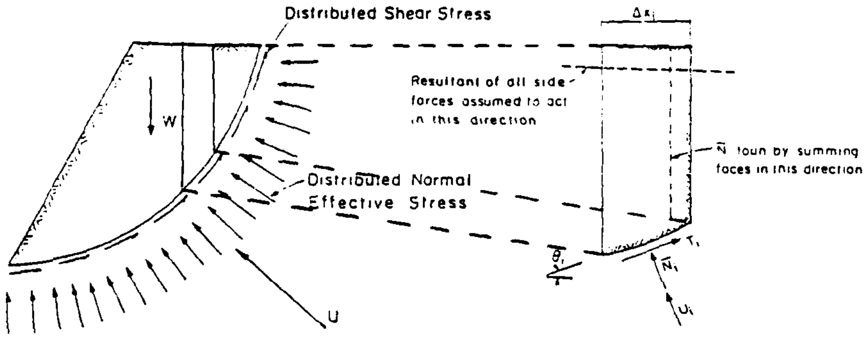

Figure 5. Simplified Bishop analysis of rotational slip toe failure

the computer program STABL2 to perform the iterative calculations for circular arc toe failures, which Osman (1985) found to be suitable for application to eroding riverbanks with gentle slopes. The calculations used in the analysis are based on the simplified Bishop method of slices This has been found to give solutions which fall within the range of equally correct solutions determined from more exact methods. It is relatively straight forward to apply, does not have excessive data requirements that would limit its applicability, and is recommended for general use in the geotechnical engineering literature (Lambe and Whitman, 1969).

1.2 Computational Methods

The calculations involved in applying the analyses of bank stability with respect to either slab or rotational slip failure are quite complicated. Therefore part of Task 1 in the study was to produce calculator and/or computer based procedures to perform the necessary calculations. Most of the banks of interest in the DEC studies are steep and are located close to knick points and so major emphasis was placed on the analysis of

slab failures. However, field observations indicate that rotational slip failures may also be significant and so the procedure for slip failure analysis is also included here.

1.2.1 Slab Failure:- Two procedures have been developed for performing the Osman-Thorne analysis of slab failures of steep eroding riverbanks.

The first uses a Hewlett-Packard HP-41CV hand-held, programmable calculator. The program prompts the user for the input data on the initial bank geometry and soil properties necessary to apply the analysis, and then outputs the initial factor of safety. The user then inputs increments of bed degradation (DZ) and/or lateral flow erosion (DW) and repeats the analysis, until the factor of safety is reduced to unity, defining the critical condition. The program then outputs the critical values of total bank height (H_{crit}), sloping bank height ($H1_{crit}$), tension crack depth (Y_{crit}), bank angle (I_{crit}), failure plane angle (BETA), lateral erosion distance (DW_{crit}), bed degradation distance (DZ_{crit}), block width (BW), and block volume (VB).

After analysis of the initial failure is completed the program moves on the analysis of subsequent failures. First, the factor of safety following the initial failure is computed and displayed, and then the user inputs increments of lateral erosion and bed degradation until the critical case is found. The program then outputs the critical parameters for subsequent failures.

A complete user's manual for the HP-41CV program (including instructions on entering and running the program, a worked example of its use, and a listing of the code) has been written, and a copy may be found in Appendix A of this report.

The second computational method uses an IBM-PC or PC compatible micro-computer and the LOTUS 123 spread sheet. The spread sheet program was written by Lyle W. Zevenbergen on the basis of the HP-41CV program. Lyle is employed by Water Engineering and Technolgy Inc. (WET), 419 Canyon, Suite 225, Fort Collins, Colorado 80521. WET is involved in the DEC study as an architect-engineer (AE) consultancy company, (see for example WET, 1987), and the findings of this study have been communicated to the staff at WET through professional contacts and the furnishing to them of quarterly reports. The PC based program is just one of the mutually beneficial products of this liaison.

To run the analysis the LOTUS 123 is set-up on the computer, and the relevant data on bank geometry and soil properties is entered into unprotected cells on the customized spread-sheet. Values of bed degradation and/or lateral erosion are then entered until the critical case is found. The critical parameters then appear on the screen, and the subsequent failure analysis part of the spread-sheet is activated. Subsequent failures are then analyzed in the same way. A hard-copy of the spread-sheet may be

generated using the PRINT command.

The PC based procedure has advantages over the HP version:-

1. The variables can be changed very easily. Any input variable (H,H',i,phi,c,gamma,or K) can be changed at will and the effect on the factor of safety seen immediately. This makes it convenient to examine the sensitivity of the factor of safety to each variable, and the change necessary to cause the bank to fail;

2. The program runs much more quickly than on the calculator;

3. Entry errors can be corrected easily without the need to start over;

4. The great computational power and memory of the PC means that the program has potential for expansion to include the effects of complex stratigraphy.

Its disadvantages are:-

1. The program cannot be run "on-site" as, unlike the HP-41CV, the PC is not portable ;

2. Availability of the PC's having the LOTUS 123 spread sheet installed is much more limited than that of HP-41CV's;

3. Although the computer and spread sheet are quite "user friendly", some familiarity with the system in use and the spread sheet software is essential to installing and running the analysis successfully.

Those interested in using this procedure must have proper access to LOTUS 123 and should write to the originator, Lyle Zevenbergen, at the above address, for permission to copy the and use the customized spread sheet.

1.2.2 Rotational Slip:- The computational procedure for the simplified Bishop analysis was developed by using the sub-routine CIRCL2, of the program STABL2, to generate stability numbers, $n_s = c/gH$, as a function of the bank angle (i) and the friction angle (phi). The stability number is then plotted against the ratio of critical bank height to actual bank height (H_c/H), for each bank angle, with friction angle held constant. A suite of curves (one for each friction angle) results. The process is then repeated for the next bank angle. A family of stability charts results for banks having angles of between 30 and 60 degrees, in 5 degree increments. For intermediate values of phi and i, critical bank height (H_c) is estimated by interpolation .

The stability charts, user instructions, and a worked example may be found in Appendix B.

2. DATA ASSIMILATION

2.1 Data Requirements

The data listed in Table 1 are needed to apply the bank stability analyses.

Table 1 Data Required for Analysis of Bank Stability

Variable	Symbol	Units
Total Bank Height	H	ft
Upper Bank Height	H'	ft
Bank Slope Angle	i	Degrees
Bulk Unit Weight		lb/ft^3
Effective Friction Angle	'	Degrees
Effective Cohesion	c'	lb/ft^2
Tension Crack Index	K	--

The geometric variables are defined in Figs. 3 and 4. The tension crack index is defined by:

$$K = Y/H \tag{1}$$

where, Y = tension crack depth (ft) and H = total bank height (ft). Experience shows that crack depth is usually limited to less than half the bank height and it is recommended that the analysis be restricted to K values less than 0.5. If there are no data on the depth of cracking at the site being investigated, K = 0.5 may be used as a default value.

Information on the geotechnical properties of the bank materials is often difficult to obtain. The results of test borings for the foundations of hydraulic structures may be available, or field tests may be undertaken using devices such as the Iowa Borehole Shear Tester (Thorne et al., 1981). However, in the lack of such data, values for the effective cohesion, friction angle, and bulk unit weight must be estimated from the soil description and stratigraphy of the banks and this can be a major source of uncertainty in applying the analysis.

Failure usually occurs during "worst case" conditions when the strength of the bank materials is minimized and their weight is maximized. Such conditions are associated with periods of prolonged rainfall, snowmelt, and drawdown following high flow stages in the channel. At such times there may be excess positive pore water pressures in the banks, which further weakens them. In the stability models, "worst case" conditions may be represented by using the lowest values observed for the effective cohesion and friction angle, together with the saturated bulk unit weight. This seems to reproduce the *in situ* strength

behavior of the bank materials under "worst case" conditions adequately, without the need to know the actual distribution of pore pressure. The requirement to know the pore pressure distribution at the time of failure would severely limit the usability of the model because such data are in practical terms unobtainable for real riverbanks outside experimental watersheds.

Banks which are stable under "average" conditions but are unstable under "worst case" conditions are at risk of failure. Although they may appear to be quite stable on inspection during good weather, their stability cannot be relied upon and they may be expected to fail during or after the next storm or period of high discharge.

2.2 Data Sources

At the beginning of the study it was recommended by staff in the Hydraulics Section of the Vicksburg District, Corps of Engineers (LMK) that the bank stability analysis be primarily applied to the Long Creek Watershed. Consequently, data assimilation has centered upon Long Creek and its tributaries.

Long Creek watershed is located in Panola County, Mississippi (Fig. 6). It is one of six watersheds currently involved in the DEC project. Long Creek enters the Yocona River just downstream of Enid Reservoir. It has a drainage area of 55,000 acres, of which 12,000 acres are in row crops, and 18,000 acres are in pasture. In common with many of the streams that drain from the bluff-line hills into the Yazoo Basin, Long Creek and its tributaries have experienced severe degradation and widening over the last fifteen years.

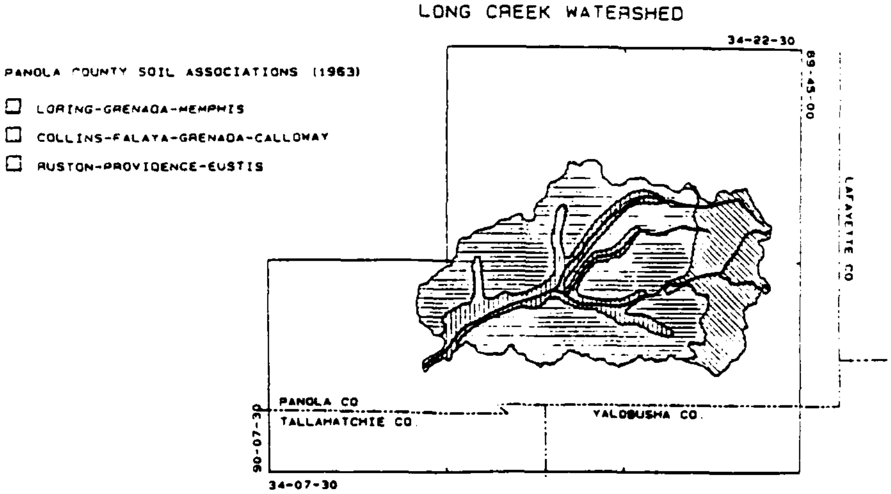

Figure 6. Long Creek watershed, Panola County, Mississippi (From a map supplied by W.C. Little, ARS Sedimentation Lab.)

2.2.1 **Bank Geometry Data**:- Channel changes have been documented by the LMK through surveys of the trunk stream and a number of tributaries. The long-profiles and cross-sections from these surveys were used as the main data base for information on bank heights and angles. The locations and dates of the surveys used are listed in Table 2.

Bank heights and angles were extracted from the plotted cross-sections by Lisa Cheadle, a graduate student from Queen Mary College, who visited Mississippi during the period November 1987 and January 1988 as a research assistant on the project.

Table 2. Locations and Dates of Channel Surveys in the Long Creek Basin used to Generate Bank Height and Angle Data

Creek Name	Range/Location	Date
Long Creek	009+00 - 370+00	Dec. 1976
	386+00 - 587+00	Aug. 1977
	009+00 - 370+00	Jan. 1979
	000+00 - 373+00	Sep. 1985
	Site #1	Nov. 1985
	Site #2	Nov. 1985
	Site #2	Dec. 1986
	Site #3	Dec. 1986
Caney Creek	020+00 - 227+00	Mar. 1977
	000+00 - 248+00	Aug. 1985
	C1 - C5	Nov. 1985
	Site #2 CC-1 - CC9-6	Dec. 1986
	Site #3 CC-1 - CC3-0	Dec. 1986
Goodwin Creek	001+00 - 184+50	Mar. 1977
	205+00 - 304+46	Aug. 1977
	002+00 - 268+00	Sep. 1985
Johnson Creek	026+00 - 222+00	Mar. 1977
	249+00 - 616+00	Jul. 1977
	137+00 - 222+00	Jun. 1979
	005+00 - 525+00	Sep. 1985
Peters Creek	001+44 - 342+00	Mar. 1977
	005+00 - 349+00	Oct. 1985
Bobo Bayou	005+00 - 131+00	Oct. 1985
Hurt Creek	005+00 - 272+00	Nov. 1985
Pope Creek	TW6+00 - 130+00	Nov. 1985

2.2.2 **Bank Material Properties:-** The banks of Long Creek are formed in stratified alluvium. Th stratigraphy is similar to that in many of the bluff-line streams. The nature, age, and origin of the various stratigraphic units has already been studied intensively (Grissinger et al., 1981 & 1982; WET, 1987), and these topics are not further addressed here. In general the layers working from top to bottom are: Post Settlement Alluvium (PSA); Young Paleosol (YP) /Meander Belt II (MB II); Old Paleosol (OP)/ Massive Silt (MS), Basal Sands and Bog Deposits (BS)/ Meander Belt I (MB I).

The characteristic "worst case" engineering properties of the bank materials in the Long Creek Watershed were estimated from the results of field and laboratory tests on soil materials from two tributaries, made in an earlier study (Thorne et al., 1981). No new strength measurements were made in this study. An estimate of the average thickness of each layer as a percentage of the total bank height was made on the basis of observations of bank stratigraphy in Long Creek and its major tributaries, made during field reconnaissance trips early in the study. The percentages were then used to produce a weighted average for all bank materials. The generalized bank properties are listed in Table 3.

Table 3. Generalized Bank Material Properties for the Long Creek Watershed

Soil Unit	Percent of Bank Height (%)	Friction Angle (°)	Cohesion (lb/ft^2)	Unit Weight (lb/ft^3)	Tensile Strength (lb/ft^2)
PSA	50	12	430	123	46
MB II(YP)	20	16	317	122	106
MS (OP)	10	14	720	132	221
MB I (BS)	20	20	0	141	0
Bank Averages		16	270	130	46*

* Based only on material in upper 50% of bank, as crack depth is less than half the bank height.

3. APPLICATION TO LONG CREEK WATERSHED

3.1 Results

The analyses were applied to find the critical bank heights for initial failures of planar slopes based on the generalized bank material properties listed in Table 2. The slab-type failure analysis was used for bank angles steeper than 60 degrees, and the rotational slip analysis for banks flatter than 60 degrees. The results are listed in Table 4.

Table 4. Critical Bank Heights for the Long Creek Watershed, based on Generalized Bank Material Properties

(A) Slab-Type Failures							
Bank Angle (Degrees)	60	65	70	75	80	85	90
Critical Height (ft)	21.5	17.5	14.5	12.0	10.1	8.6	7.35
(B) Rotational Slip Failures							
Bank Angle (Degrees)	30	35	40	45	50	55	60
Critical Height (ft)	51.9	41.5	30.5	26.6	26.0	21.9	19.8

The critical heights for slab and slip failures for banks with angles in the range 55 to 60 degrees are almost the same, as expected from theory. This suggests that banks in this range should be about equally likely to collapse by either slab-type or rotational slip failure.

The line of limiting stability is plotted with the observed bank heights and angles from the Corps surveys in Fig. 7.

3.2 Discussion

Two limitations must be noted concerning use of the channel survey data to test the bank stability analysis. First, as was pointed out in the WET report on Batapan Bogue (WET, 1987), field crews tend to avoid the steepest bank sections when conducting channel surveys. They do this for the sound practical reasons that working on very steep banks is difficult, time consuming, and sometimes dangerous. Unfortunately, this introduces a bias in the data, with the steepest banks being grossly under-represented. This reduces the utility of the data for generally testing the stability model developed here.

Second, on the creeks which had been surveyed more than once, the surveyed sections rarely coincided, and the surveys were mostly several years apart. Consequently, the surveys could not be used to differentiate stable from unstable banks. Also, it was impossible to use the data to test the accuracy of the predicted factors of safety rigorously, because the surveys could not be expected to define accurately the geometry of the bank at the time of failure.

However, within these limitations, the results plotted in Fig. 7 may be used for an initial evaluation of the applicability of the stability analyses.

The observed points mostly plot in the "stable" zone on the graph. This is logical, because most of the banks were in a stable condition at the time of survey, eroding banks generally being avoided by the surveyors. The line of limiting stability seems to form a reasonable upper envelope most of the data.

Some banks do plot in the "at risk" zone, above the line of limiting stability. This suggests that these banks would fail if "worst case" conditions were to occur. Consideration of the locations and dates of the points plotting "at risk" indicates that they are mostly associated with erosion at the outside of developing bendways where rapid retreat is to be expected and it would be hard to avoid surveying eroding bank sections.

On this basis the application of the analyses to the channel survey data for the Long Creek Watershed yields results which are encouraging, but inconclusive. It was therefore decided to collect detailed field data from eroding banks to test the accuracy of the factors of safety predicted by the stability analyses, and to verify if the analyses could be used to characterize the overall conditions of bank stability throughout the Long Creek Watershed.

4. FIELD DATA COLLECTION

4.1 Site Selection

The reaches selected for testing the bank stability analyses are in a reaches known to be experiencing severe bank attack due to combinations of bed lowering and lateral erosion. Three reaches were established. Site 1 is between the old grist mill and Grade Control Structure #1 on Long Creek. This location gave the site the added potential to yield interesting information on the effectiveness of a grade control structure in reducing bank retreat and helping to stabilize the banks, by preventing toe scour. Sites 2 and 3 are at reaches investigated in the earlier study of bank stability (Thorne et al., 1981). Site 2 is at Katherine Leigh's property on Goodwin Creek. Site 3 is at Tommy Florence's property on Johnson creek. These sites were selected because of the availability of past profiles and *in situ* strength measurements from the earlier work. Site locations are shown in Fig. 8.

4.2 Data Collection

At Site 1, seventeen sections were profiled by leveling and monumented using wooden pegs on December 1, 1987. At Sites 2 and 3, six and three sections were profiled and monumented respectively, on December 2/3, 1987. The sections at all three sites were re-surveyed on January 21/22. Those at Site 1, were again surveyed on April 21, 1988.

4.3 Observed and Predicted Bank Failures

The observed bank heights and angles are plotted in Fig. 9, together with the line of limiting stability for "worst case" conditions predicted from application of the stability analyses. Predictions were based on: the bank geometries observed in the field; and the average bank parameters listed in Table 3.

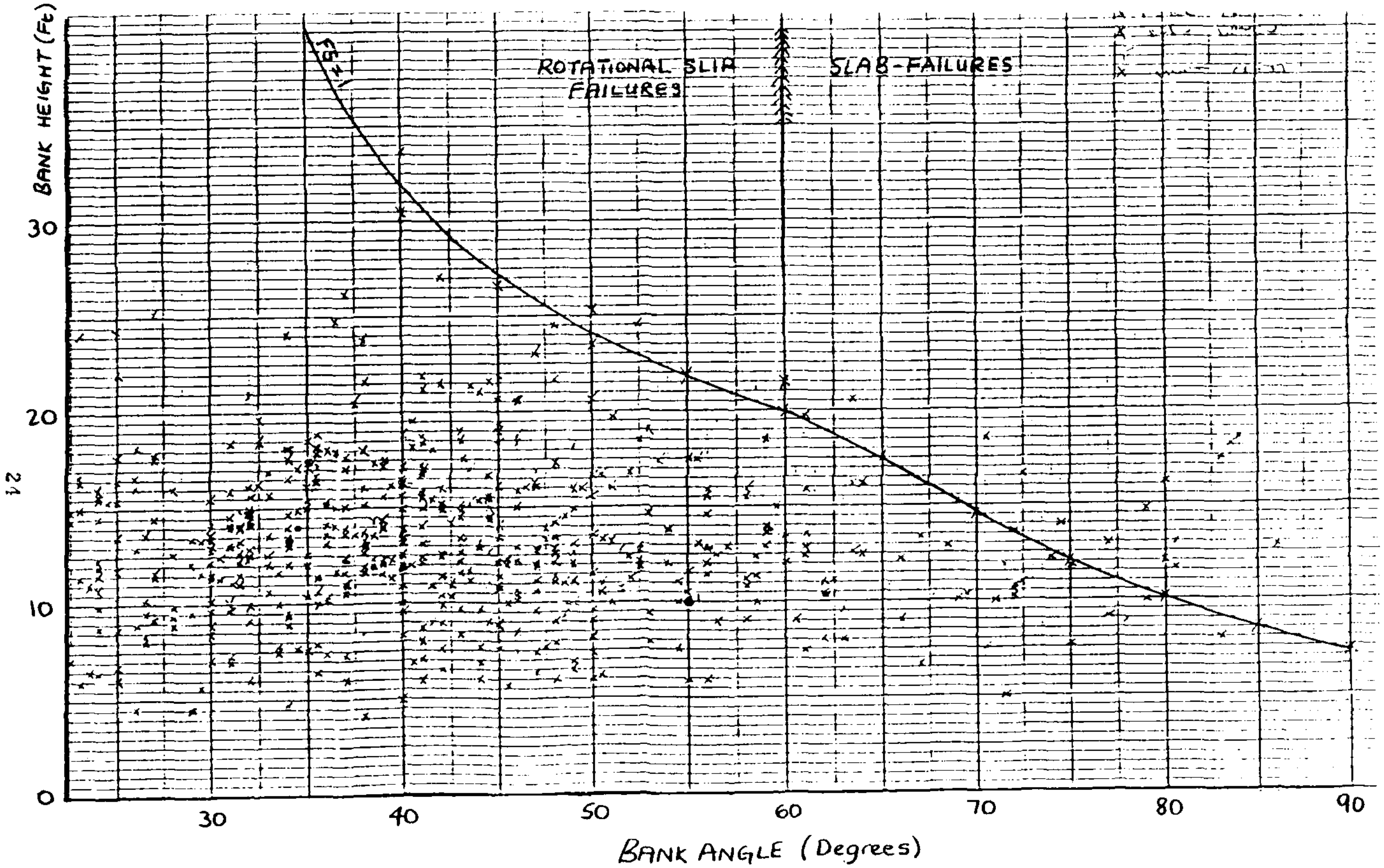

Figure 7. Observed bank heights and angles for Long Creek and its tributaries based on Corps surveys.

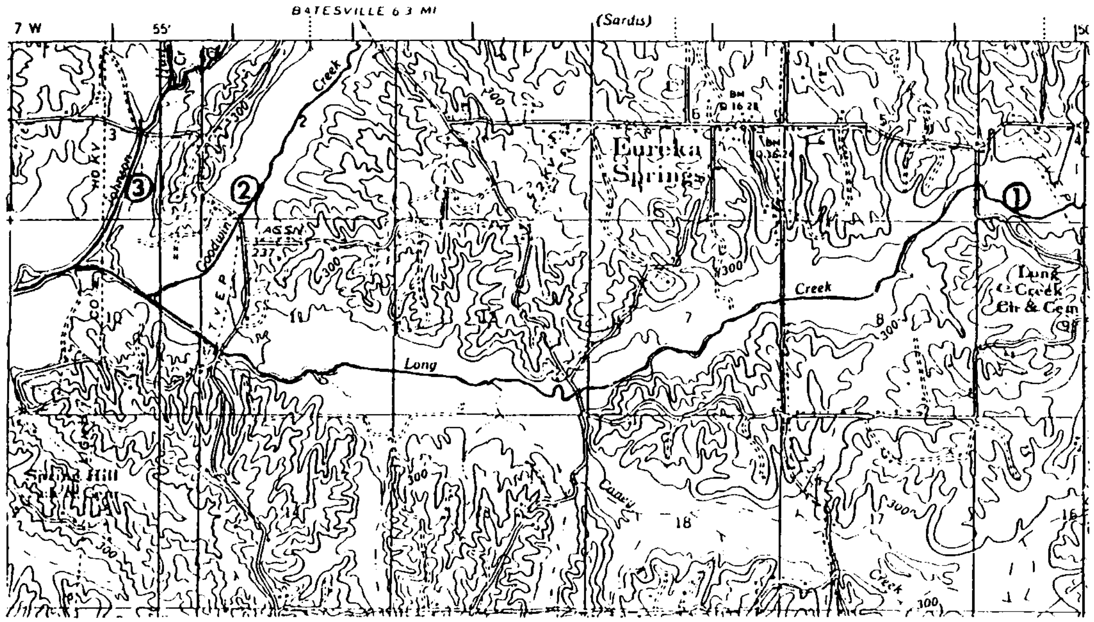

Figure 8. Location of study sites in Long Creek Watershed

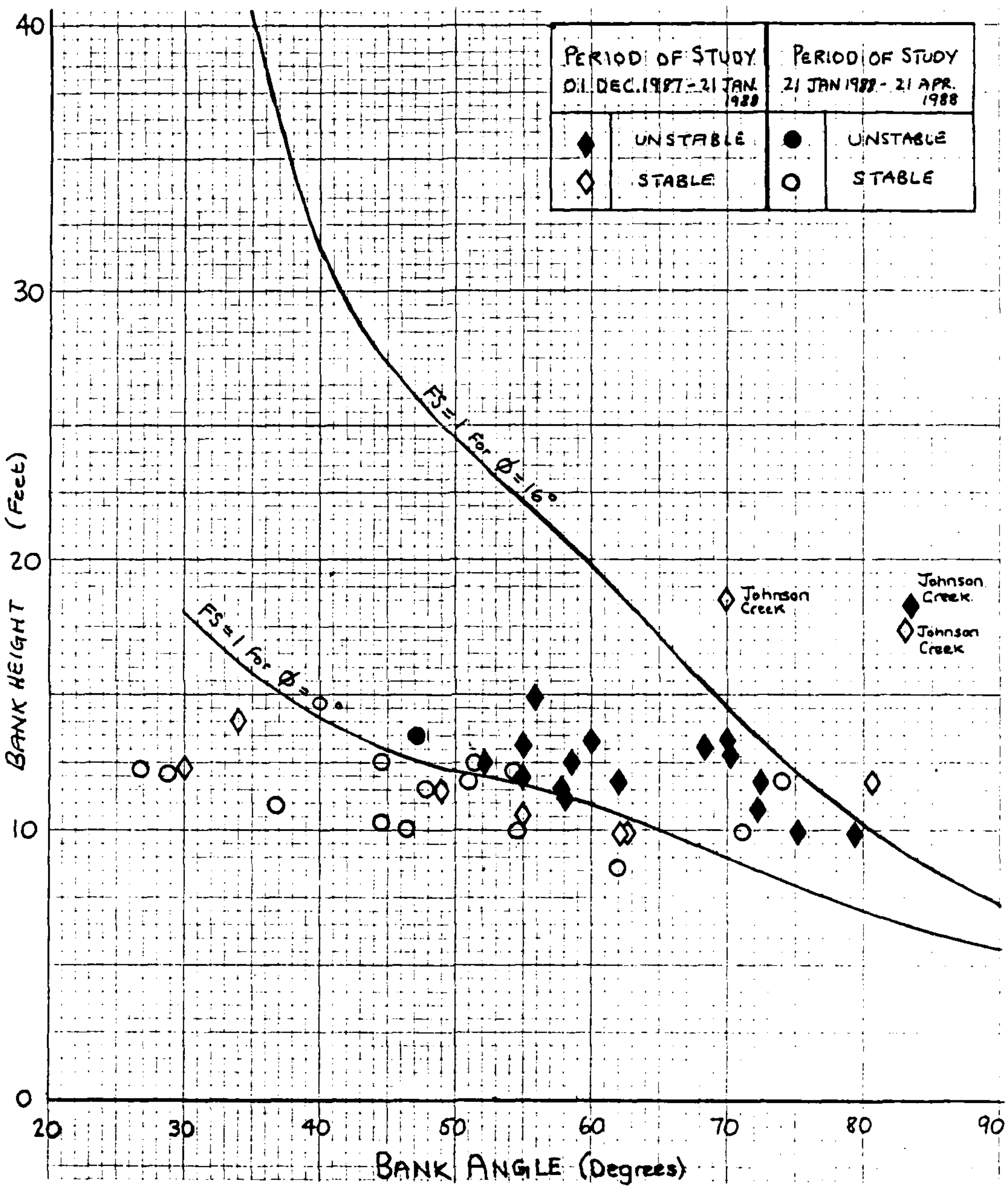

Figure 9. Bank stability plot for Long Creek Watershed field study sites

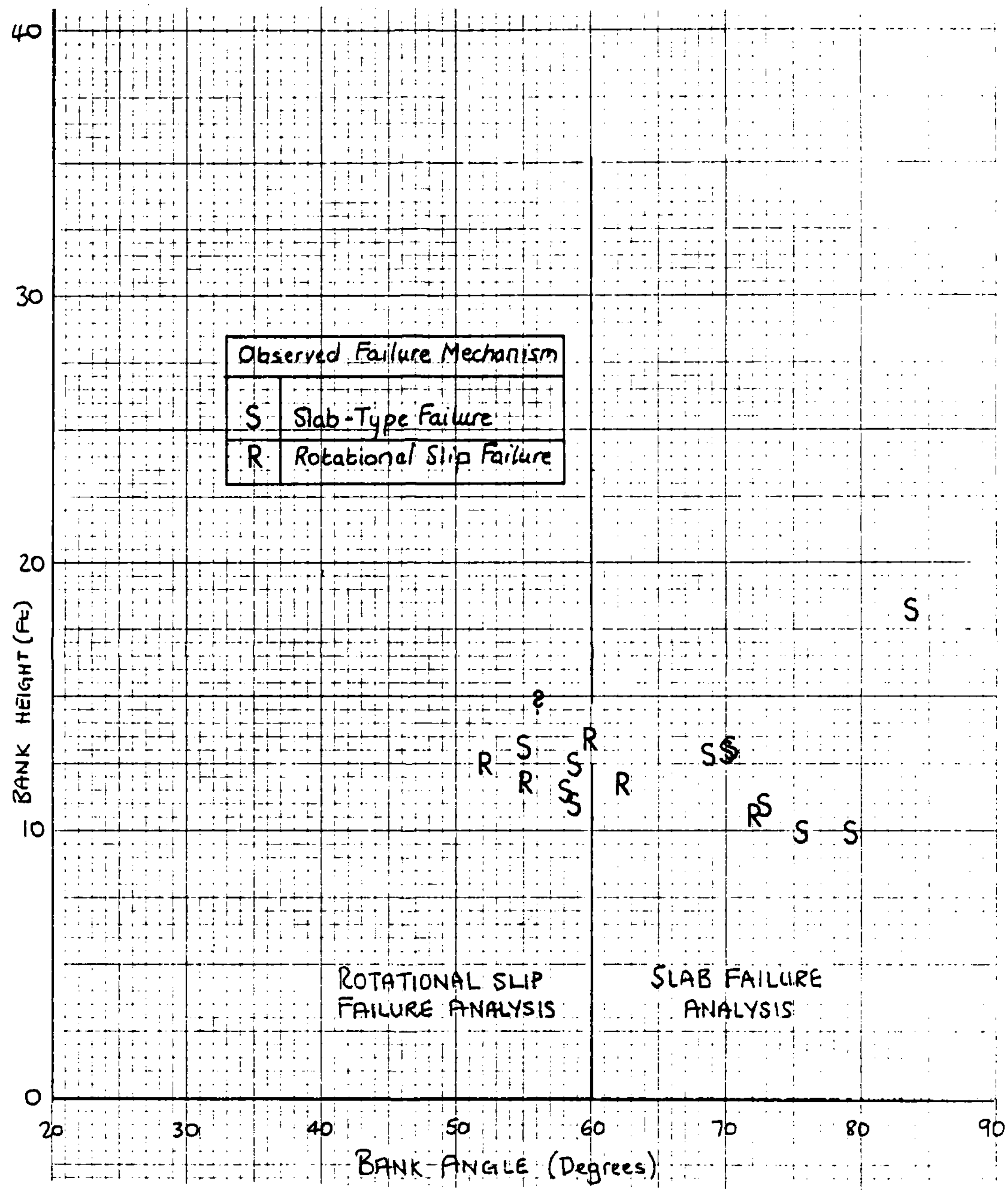

Figure 10 Observed and predicted mechanisms of failure for banks at Long Creek Watershed study sites

4.4 Discussion of Results

4.4.1 Prediction of Bank Instability:- Sixteen sections failed in the December-January period, during which the basin had experienced prolonged and heavy precipitation (both rain and snow) which would most certainly have generated "worst case" conditions in the banks at the study site. Failures were classified as either slab-type or rotational slip, on the basis of field observation of the configuration of any remnants of the failure block, together with examination of the shape of the failure surface, as represented by the January 1988 bank profile.

Fig. 10 shows that, as predicted from theory, slab-failures do indeed predominate on steep banks and rotational failures on flatter banks. In the range 55 to 65 degrees, the bank is equally likely to collapse by either type of failure. The use of the slab analysis for steep banks and the rotational slip analysis for flatter banks seems justified, therefore.

In Fig. 9 the stability curve based on basin wide estimates of the soil properties is clearly too high, because many sections that failed between December and January plot well below the line of limiting stability.

Four points do plot in the "At Risk" zone, well away from the rest of the data. Three of the points represent the three sections at Site 3, located on Johnson Creek. The bank stratigraphy at Johnson Creek in the study reach was notably different to that at the other sites or in the Long Creek Watershed in general, in that the banks consisted mostly of massive silt. Consequently, the generalized bank material properties do not represent those at this site, where the banks are much stronger. This was also observed in the 1981 study. Significantly, many of the points which plot "At Risk" in Fig. 7 also come from Johnson Creek. The data from Johnson Creek are, therefore, considered separately from those from Long and Goodwin Creeks. One point from Long Creek plotted "At Risk". It was stable during the Dec-Jan period. This section was located where a thick outcrop of massive silt created a hard point jutting out into the channel. It is also, therefore, not directly comparable to the rest of the sections.

In the field in January, it was noted that at many locations the bank toe in the region of the failure surface was fully saturated and that it was very slick. Water draining through the banks encounters the massive silt (which is mostly located low in the banks at the study sites) and ponds there because low hydraulic conductivity of the massive silt compared to the MB II and PSA layers above it. This generates saturated conditions that lubricate the potential failure surface, and positive pore water pressures and seepage forces, which further reduce the effective friction angle. In the limit, the frictional contribution to soil strength becomes negligible.

The analyses were therefore repeated, this time using a friction angle of zero. The resulting critical bank heights are listed in Table 5. The line of limiting stability for phi=0 is an

excellent discriminator between stable and unstable banks during the December-January period.

Table 5 Critical Bank Heights for Long Creek Watershed, based on reduction of effective friction angle to zero

(A) Slab-Type Failures							
Bank Angle (Degrees)	60	65	70	75	80	85	90
Critical Height (ft)	11.3	10.0	8.9	7.9	7.0	6.2	5.55
(B) Rotational Slip Failures							
Bank Angle (Degrees)	30	35	40	45	50	55	60
Critical Height (ft)	18.1	16.0	13.8	13.0	12.2	11.5	10.9

In the second study period only one bank failure occurred. The stable banks plot mostly below the limiting stability line for phi=0 in Fig. 9., but four points plot between this line and that for phi=16 degrees. These banks were stable during the second period only because the conditions of very high moisture content and strong basal seepage necessary to trigger failure by lubricating the potential failure surface did not occur. Their stability is then unreliable as they could fail without any further toe erosion.

4.4.2 Effect of Long Creek Grade Control Structure:- In the field, the effect of the grade control structure is evident in that the amount of sediment accumulation in the bed and the degree of basal scour of the banks both decrease in the downstream direction as the back-water area of the structure is entered. Sections are numbered consecutively downstream. In the December-January period, sections 1 to 9 all experienced active toe erosion, leading to bank failure at sections 1,3,4,5,6,7 and 9. Section 10 experienced no change in basal elevation. It failed because it was already "At Risk" in December 1987 and did not need further toe erosion to cause it to fail. The lower sections (11 to 17) actually showed basal accumulation due to sediment deposition behind the grade-control structure. This was anticipated in the design and in fact the invert of the structure was set 4 feet above the bed to induce deposition and bed aggradation. This has had the effect of maintaining sections 11,12,14 and 15 in a stable condition with respect to mass failure. Failures did occur at sections 13,16 and 17, but the failed sediment was not removed by the flow, as it was further upstream. Instead, it accumulated as a berm at the toe. In the January-April period there was hardly any toe attack throughout the reach, but aggradation, basal accumulation and berm building

continued downstream of section 11. 'though some further, shallow seated slope failures and some s] :rosion due to sub-aerial processes will occur on the ban. sections 11 to 17, the stability analyses, taken together with the concept of basal endpoint control of bank retreat rate by the flow, suggest that the downstream 7 sections in this reach should not experience further serious retreat because of the stabilizing effect of the structure on the bank toes. In the upper reach toe scour is continuing because the back water does not extend to this reach and because the banks are located at the outside of a developing bendway hat brings the thalweg close to the outer bank. These banks will continue to retreat until either sediment deposition induced by the structure stabilizes the bank toe, or there is a chute cut-off behind the point/mid bar that directs the flow to the outside of the bend.

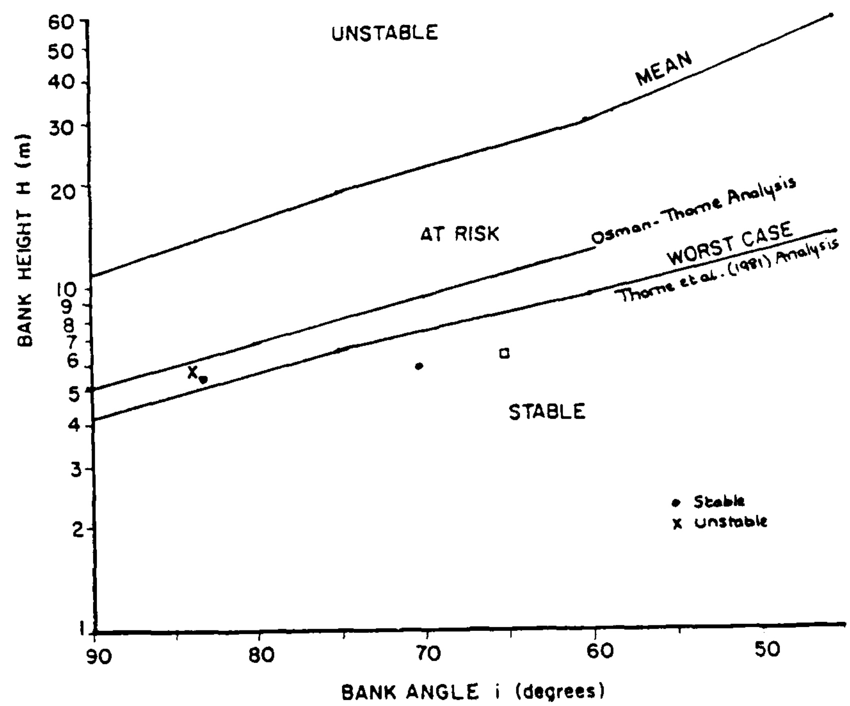

Figure 11 Bank Stability Chart for Johnson Creek at Tommy Florence Site, section 4 (Site 3 in this study)

4.4.3 Bank Stability at Johnson Creek Site:- In the 1981 study (Thorne et al., 1981) detailed strength measurements were made at the site on Johnson Creek. The data were used to produce the stability chart shown in Fig. 11.

The Osman-Thorne analysis for slab-type failure was applied to the site using the characteristic data reported in the 1981 study:

effective cohesion,	c'= 650	psf
effective friction angle,	phi'= 13.8	degrees
saturated bulk unit weight,	gamma = 133	pcf
tension crack index,	Y = 0.5	

to produce the line of limiting stability shown in Fig. 11. The data points corresponding to the banks surveyed in 1981 and in this study have been added to Fig. 11. The Osman-Thorne line of limiting stability in Fig. 11 is close to that from the Thorne et al. report and is in reasonable agreement with the observed condition of the banks, which of marginal stability.

5. ENGINEERING APPLICATIONS IN THE DEC WATERSHEDS

The analysis developed in the 1981 study (Thorne et al., 1981) has already been incorporated into engineering/geomorphic models for the evolution of degrading streams in the DEC watersheds (WET, 1987). On Hotopha Creek the line of limiting stability was found to discriminate between stages of channel evolution during which the banks were or were not stable with respect to mass failure.

In the WET five stage model, the conditions of bank stability associated with each type of channel are as follows:

Type I	Bed stable or degrading - Banks stable, FS >> 1
Type II	Bed degrading - Bank stability marginal, FS 1
Type III	Bed degrading or stable - Banks failing, FS < 1
Type IV	Bed aggrading - Banks Stabilizing, FS 1
Type V	Bed stable or aggrading - Banks stable, FS > 1

On Hotophia Creek, channel types 1, 4 and 5 plotted below the Thorne et al. (1981) line of limiting stability, while types 2 and 3 plotted above it, but it was not possible to split the types beyond this.

If the Osman-Thorne analysis presented here is used in a similar fashion in future analyses, it should be possible to better define the channel type/bank stability association. In particular, the following distribution of plotting points might be hypothesized:

1. The banks of type I and type V channels will plot in the "Stable" zone,below the line of limiting stability for phi = 0 (see Fig. 12). This means that failures are unlikely;

2. The banks of type III channels will plot in the "Unsafe" zone, above the line of limiting stability for phi = 16 degrees. This means that bank failures probably occur several times a year;

3. The banks of type II and IV channels will plot in the "Unreliable" zone between the lines of limiting stability for phi = 0 and phi = 16 degrees. This means that failures may occur, but not as frequently as for type III channels. Bank stability is in a state of transition. In type II channels the probability of bank failures is increasing through time as the channel moves towards a type III configuration. In type IV channels the probability of failures is decreasing through time as a type V channel develops.

4. Reaches trunk stream or tributaries with thick layers of massive silt in the lower bank will plot close to the line of limiting stability for the Johnson Creek site. Isolated masses of massive silt will form hard points jutting out into the channel, with locally steep bank angles.

More recently, in the analysis of Batapan Bogue, the slab failure analysis of Thorne et al. (1981) is used to quantify the geotechnical stability of the bank, using a parameter, N_g. N_g is defined as the ratio of the actual bank height at the actual bank height, to the critical bank height for that angle, as determined from the bank stability analysis. This does not account for the effects of toe erosion in increasing the angle of the bank at the same time as its height and so an additional stability number is also proposed. This is N_{g90}. In this number, the denominator is the critical bank height for a vertical bank. This would tend to be on the conservative side in predicting bank stability. No separate analysis is used for rotational slip failures.

There seems no reason why the Osman-Thorne bank stability analyses for slab and rotational slip failures should not replace that currently used in the N_g calculations. This would have several advantages:

1. Although still relatively unsophisticated, the Osman-Thorne analyses have a sounder theoretical basis than the Thorne et al. (1981) procedure;

2. The new analyses account for slab and rotational failures separately;

3. Computerized calculation procedures are available for the Osman-Thorne analyses;

4. The Osman-Thorne analysis of slab-type failure accounts for the effects of toe erosion in change both the bank height and geometry through the DW and DZ inputs that increase the total bank height (H) and decrease the sloping bank height (H') until the limiting geometry is reached;

5. For the Long Creek Watershed, testing the analyses against field data indicates satisfactory agreement between observed and predicted bank stability.

It is therefore proposed that the Osman-Thorne analyses should be used as an integral part of the on-going engineering and geomorphic studies of the DEC Watersheds.

IV CONCLUSIONS AND RECOMMENDATIONS

Application of the Osman-Thorne analyses to the Long Creek Watershed shows that it is possible to make a broad assessment of bank stability on the basis of gross estimates of the bank material properties throughout the watershed. However, the results for Johnson Creek indicate that it may not always be possible to use a single set of parameters to represent the bank material characteristics throughout a large watershed. Different tributaries or even reaches of the trunk stream may have significantly different bank stratigraphies that necessitate a separate analysis. From other data not presented in this report because of space limitations, it appears that Caney Creek may, like Johnson Creek, fall into this category because significant reaches of that creek have significantly stronger banks than average for the basin.

The contribution of friction to bank strength is unreliable in Long Creek, because of the possibility for lubrication of the potential failure surface be water seepage at the contact between the Meander Belt II (YP) and Massive Silt (OP) when this contact is located low in the bank. Therefore in synthesizing the results of this study into a single stability plot, the "At Risk" zone has been split into two (Fig. 12).

Banks plotting below the line of limiting stability for the friction angle equal to zero should be stable. They would still be susceptible to erosion be overbank field drainage, however, and might experience some minor, shallow, seated slope failures. But provided that they do not experience renewed toe erosion by the flow banks plotting in this zone should not retreat seriously.

Banks plotting in the "Unreliable" will only fail if heavily saturated. This happened widely in the period December 2, 1987 to January 21, 1988, but that period included a heavy snowfall, a rapid melt, abundant rainfall, and high flow stages in the channel. This was an exceptionally harsh test of bank stability in the basin. Banks plotting in this zone are potentially unstable, will fail perhaps once a year on average, and will continue to retreat so long as the stream continues to remove the slump material from the bank toe.

The results from the study site on Long Creek are encouraging, though as they show that these banks quickly stabilize once toe erosion is curtailed (in this case by backwater deposition behind the grade control structure).

Banks plotting in the "Unsafe" zone will fail several times a year provided that fluvial activity at the base keeps pace with the supply sediment from bank failures, so that berms do not accumulate. There is a greater probability of failure for banks in this zone than for those in the "Unreliable" zone even though banks in both zones are "At Risk". That is the banks in both the "Unreliable" and "Unsafe" zones of the stability plot are liable to fail without further toe erosion. At the level of a Watershed

wide analysis of bank stability it is not possible to be more specific than this.

The sensitivity of banks plotting in the "Stable" zone to destabilization by flow erosion and/or degradation can be assessed using the Osman-Thorne analyses. Starting with the present (stable) geometry increments of lateral erosion (DW) and /or bed degradation are entered into the analyses and the effect on the factor of safety is noted. In this way the analysis can be used to determine whether the passage of a headcut through a stable reach (WET, type I or type IV) is liable to result in bed lowering alone (WET, type II channel) or, more seriously, is liable to result in bed lowering and rapid widening (WET, type III condition).

Some reaches of the trunk stream and its tributaries may require separate analysis based on different bank material properties or stratigraphies. On Fig. 12 an additional line of limiting stability has been drawn for Johnson Creek. This line is representative of banks with large thicknesses of massive silt (OP) in the lower bank. Continuity of the extra stability of such banks is entirely dependent on the thickness of the massive silt in the lower bank. Once bed degradation breaks through the massive silt and reveals the meander belt I materials (sands and bog deposits), the operational strength of the banks reverts to something close to the gross average for the basin, as represented in the case of Long Creek by the data in Table 3.

The result is that the banks fail soon after the massive silt is breached at the toe. The morphological response is for the bank height to remain constant, with the bank angle being reduced from about 70-80 degrees to about 55-60. This has the effect of moving the plotting point for the bank close to the line of limiting stability for watershed wide bank properties, which include MB I (BS) as the basal layer (Table 3).

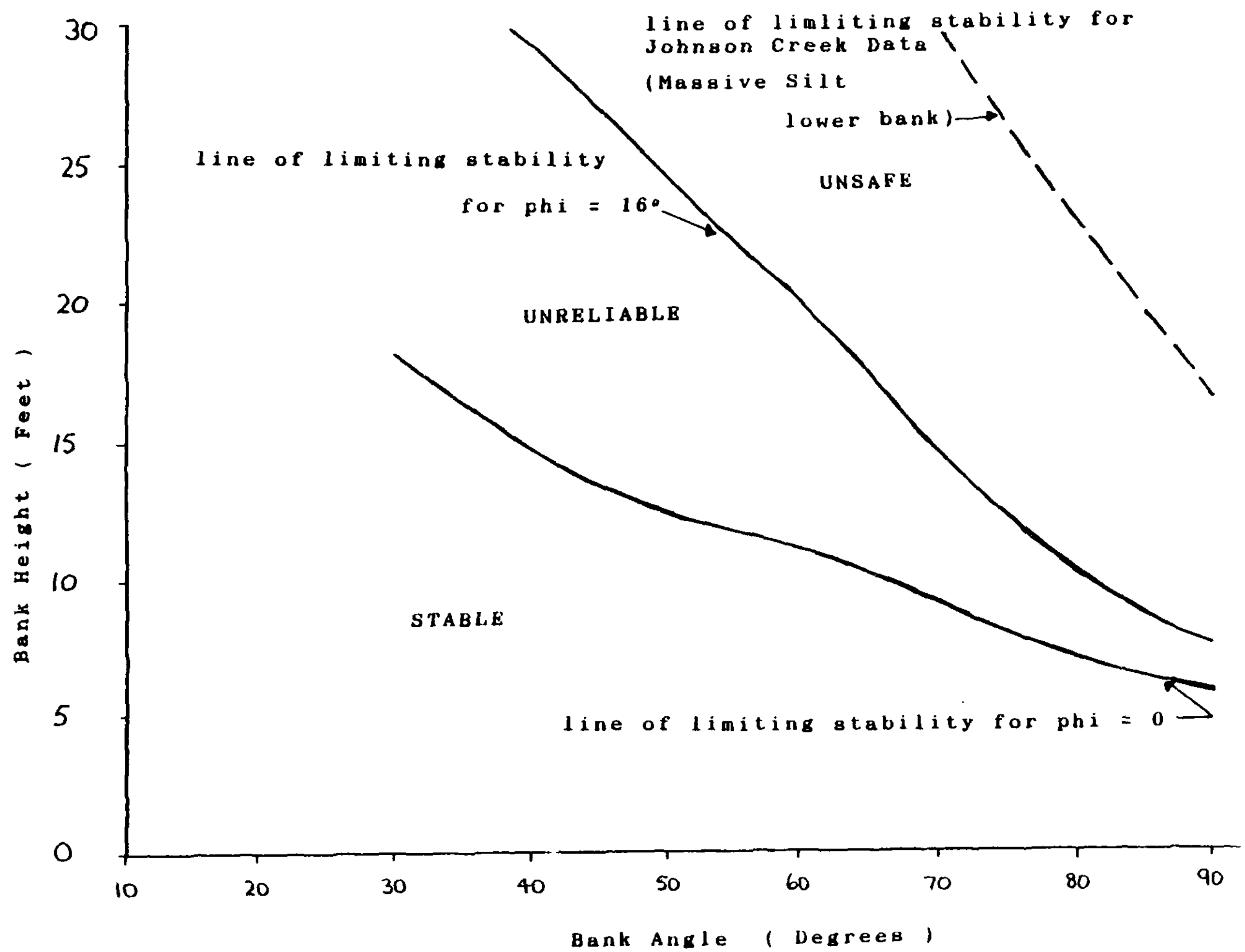

Figure 12 Generalized bank stability chart for Long Creek Watershed

V ACKNOWLEDGMENTS

This study was undertaken while the author was a visiting scientist at the US Army Waterways Experiment Station. The help and encouragement of the staff at WES are gratefully acknowledged. The project was funded by the Vicksburg District, Corps of Engineers (LMK).. The support of Phil Combs and David Biedenharn at LMK made this work possible.

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VII LIST OF PUBLICATIONS

To date, the following publications have resulted entirely or in part from the work undertaken in this project:

Osman, A.M. and Thorne, C.R. "River bank stability analysis" Journal of Hydraulic Engineering, ASCE, Vol. 114, No. 2, 1988.

Thorne, C.R. and Osman, A.M. "River bank stability analysis: II Applications" Journal Hydrau. Eng., ASCE, Vol. 114, No. 2, 1988.

Thorne, C.R. and Osman, A.M. (1988) "The influence of bank stability on regime geometry of natural channels" International Conference on River Regime, 18-20 May 1988: Wallingford, England

"Thorne, C.R., Biedenharn, D.S. and Combs, P.G. (1988) "Riverbank instability due to bed degradation" Proc. ASCE Hydraulics Conf., Colorado Springs, Co, Aug. 8-12, 1988.

Thorne, C.R., Chang, H.H. and Hey, R.D. (1988) "Prediction of hydraulic geometry of gravel-bed streams using the minimum stream power concept" International Conference on River Regime, 18-20 May 1988: Wallingford, England

VIII APPENDIXES A & B

APPENDIX A

CALCULATOR PROGRAM FOR ANALYSIS OF SLAB-TYPE FAILURE OF STEEP ERODING RIVERBANKS

CALCULATOR PROGRAM FOR ANALYSIS OF STREAMBANK STABILITY

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1 INTRODUCTION

Streambank retreat usually occurs by a combination of flow erosion and mass failure. Bank failures occur when erosion of the bank and the bed adjacent to the bank increase the height and angle of the bank so that it reaches a condition of limiting stability. The mechanism of failure depends on the geometry of the bank and engineering properties of the bank material (Thorne,1982).

Eroding banks are usually steep and commonly fail by a slab-type mechanism, where a block of soil topples forward into the channel (Figs.1 & 2). The weakening effects of tension cracks between the block and the bank can be important in triggering failure and should be accounted for when analysing the stability of this type of bank.

Figure 1. Slab failure of a streambank in Northwest Mississippi.

Failures usually occur during "worst case" conditions, when the strength of the bank materials is minimised and the weight is maximised due to high moisture levels. Such conditions are associated with periods of prolonged rainfall, snowmelt, and drawdown following high flow stages in the channel. Banks which are stable under "average" values for soil properties, but which are unstable for "worst case" conditions are at risk of failure. That means that their stability cannot be relied upon and they may be expected to fail sometime in the near future.

The analysis of the stability of streambanks with respect to slab failure was undertaken by Thorne, Murphey and Little (1981). Recently, Osman and Thorne (1988)

have developed an improved approach to this problem. The method uses the resolution of driving and resisting forces in static equilibrium on the most critical potential failure plane to derive a factor of safety (FS) for a bank with respect to slab failure. A value of FS greater than one indicates stability, and equal to one indicates the critical condition with the bank on the point of failure. Values less than one suggest that the bank is unstable and should have failed already.

Initially, the bank has the simple geometry shown in Fig.2a. Erosion and bed degradation operate to bring it to the critical condition with the characteristic geometry shown in Fig.2b.

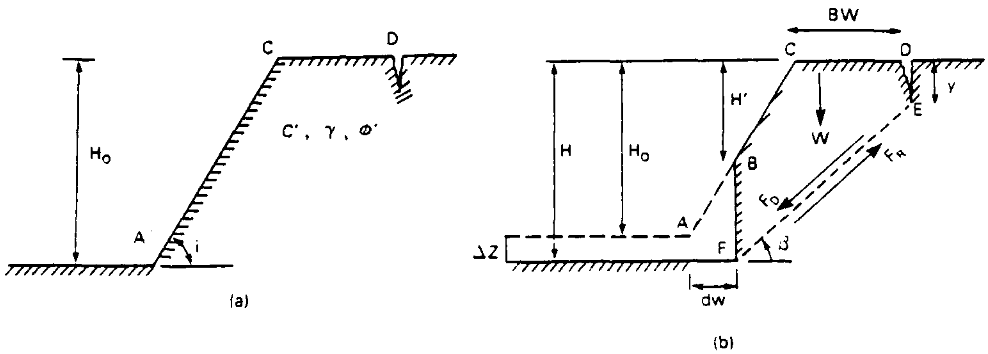

Figure 2. Definition diagram for initial slab failure analysis: a) Initial geometry; b) After erosion and degradation to the critical condition

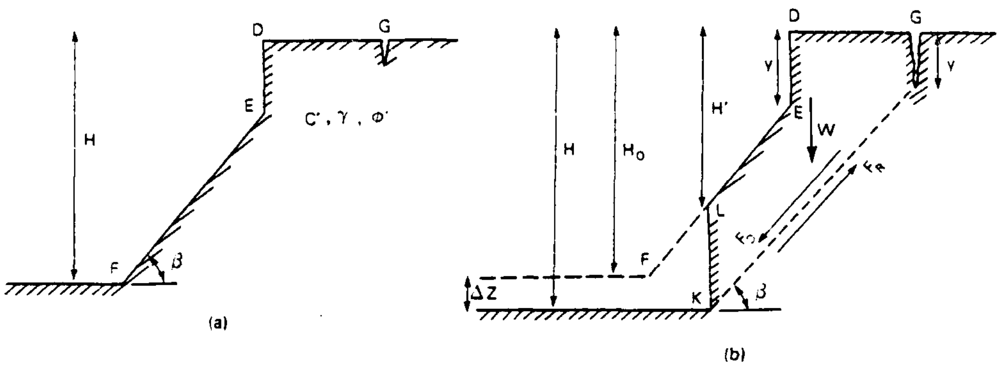

Figure 3. Definition diagram for subsequent slab failures: a) Geometry following initial failure and basal clean-out; b) After erosion and bed degradation to the critical condition

Following the initial slab failure, the bank is stable in its new configuration (Fig.3a). Failed material in a disturbed state comes to rest at the foot of the bank and it remains there until it is removed by the flow in the channel. This is the basal clean-out phase of bank retreat. After removal of the disturbed bank material, the flow again attacks the intact bank material, and lateral erosion

recommences. Field observations support the contention that further degradation of the bed is limited once the critical bank height for mass instability is reached. Further bank failures are due mostly to lateral erosion and oversteepening of the already over-heightened banks. That being the case, the bank angle may be approximated by the failure plane angle from the initial failure, and the bank retreats by parallel retreat when lateral erosion reduces the H1 to the critical value for slab failure (Fig.3b).

This User's Guide provides a calculator program for the Hewlett-Packard HP-41CV or CX calculator, which may be used for on-site application of the Osman-Thorne analysis for initial and subsequent failures. The HP-41C may be used provided that it has a quad memory module fitted.

The Guide explains how to load the program and use it to calculate the factor of safety for an initial bank, and how find the amounts of flow erosion and bed degradation which would cause the bank to fail. These parameters are measures of the vulnerability of the bank to retreat by mass failure. Critical values of the bank height, tension crack depth, bank angle, failure plane angle, block width, and block volume for initial and subsequent slab failures are computed. These parameters define the critical and post-failure bank geometries, the amount of top bank retreat, and the volume of slumped material input to the channel by each failure. No prior experience with the HP-41 is necessary.

2 DATA REQUIREMENTS

The data listed in Table 1 are needed to perform the analysis.

Table 1 Data Required for Analysis of Bank Stability

Variable	Symbol	Units
Total Bank Height	H	ft
Upper Bank Height	H1	ft
Bank Slope Angle	I	Degrees
Specific Weight	Sp.Wt.	lb/ft^3
Effective Friction Angle	phi	Degrees
Effective Cohesion	c	lb/ft^2
Tension Crack Index	K	--

The tension crack index is defined by:

$$K = Y/H \tag{1}$$

where, Y = tension crack depth (ft) and H = total bank height (ft). Experience shows that crack depth is usually limited to less than half the bank height. If there are no data on the depth of cracking at the site being investigated, K = 0.5 may be used. The variables are defined in Figures 2 & 3.

Information on the geotechnical properties of the bank materials is difficult to obtain. The results of test borings for the foundations of hydraulic structures may be available, or field tests using devices such as the Iowa Borehole Shear Tester can be used (Thorne, Murphey and Little, 1981). However, lack of data characteristic values for the intact effective cohesion, friction angle , and bulk unit weight of bank materials is a major problem.

3 LOADING THE PROGRAM

First check if the program is already in the calculator. To do this key in:

XEQ ALPHA USFS ALPHA

if the calculator responds:

NONEXISTENT

then you must load the program as described in subsections 3.1 and 3.2.

If the program is initiated and displays:

COLIN THORNE-BANK ANALYSIS
STEP NO. 1.
H ? FT

then you may go straight to section 4.

3.1 Keying in the Program

1. Turn on the calculator
2. Key in SHIFT GTO . .
3. Put the calculator in Program mode
4. Key in the program exactly as listed in Appendix 1.

Note,

i) All statements followed by either ARCL or PROMPT are entered in ALPHA mode. To select this press the ALPHA key. To complete entry press ALPHA again.

ii) Commands not found on the keyboard (for example PROMPT, PSE) are entered by keying;

XEQ ALPHA command ALPHA

for example to key in the command "PROMPT" the sequence is;

XEQ ALPHA PROMPT ALPHA

iii) The symbol, ⊢ , means APPEND and is keyed in by;

ALPHA SHIFT K ----- ALPHA

for example to key in the units that follow an output variable the sequence is;

ALPHA SHIFT K FT ALPHA

iv) The SHIFT key is yellow.

To successfully key-in the program is straight forward for those familiar with HP calculators. It represents a challenge to any individual who has not programmed an HP before, and some assistance may be required by such individuals at this stage. Loading the programs from cards is simple and is the recommended way to load the program.

3.2 Loading the Program from Magnetic Cards

If you have the program on magnetic cards and have a card reader, load the program as follows:

1. Turn on the calculator
2. Key in GTO . .
3. Ensure the calculator is *NOT* in Program mode
4. Insert the cards into the card reader
5. When all cards have been accepted, key in GTO ..

The program is now ready to run.

4 RUNNING THE PROGRAM

4.1 Keystrokes and Recording Results

After loading the program is initiated by keying:

XEQ ALPHA USFS ALPHA

After that it is only necessary to press the RUN/STOP (R/S) key to proceed, entering data as prompted by the calculator and noting output data on the record sheet, Table 2. The user instructions are listed below.

STEP	INSTRUCTION	INPUT	FUNCTION		DISPLAY
1	Initialize program		XEQ USFS		COLIN THORNE- BANK ANALYSIS STEP NO. 1. H ? FT
2	Input total height	H	R/S		H1 ? FT
3	Input upper height	H1	R/S		I ? DEG
4	Input bank angle	I	R/S		SP.WT ? LB/FT3
5	Input specific wt.	Sp.Wt	R/S		PHI ? DEG
6	Input friction angle	phi	R/S		C ? LB/FT2
7	Input cohesion	c	R/S		K ?
8	Input crack index	K	R/S		FS=_____
9	Displays Factor of Safety for initial bank geometry		R/S	A: B:	BANK STABLE H = CRITICAL
10	Displays A or B If A, continue If B, go to step 20				

	Indicates bank is below critical height.No failure will occur without erosion and/or degradation		R/S	STEP NO.__
11	Displays number of current step		R/S	DW ? FT
12	Input lateral erosion distance	DW	R/S	DZ ? FT
13	Input degradation depth	DZ	R/S	H=____FT
14	Displays new H		R/S	H1=___FT
15	Displays new H1		R/S	I =___DEG
16	Displays new I		R/S	FS=____
17	Displays new FS		R/S	A: BANK STABLE B: H = CRITICAL C: BANK TOO HIGH
18	Displays A,B,or C If A, go to step 11 If B, go to step 20 If C, continue			
	Indicates DW &/or DZ were too large so bank geometry is unstable and could not exist		R/S	REDUCE DW + DZ
19	Indicates reduced DW &/or DZ values must be used and step repeated		R/S	STEP NO.__
	Returns to step 11			
20	Indicates bank is on point of failure		R/S	H CRIT=___FT
21	Displays critical H		R/S	H1CRIT=___FT
22	Displays critical H1		R/S	Y CRIT=___FT
23	Displays critical Y		R/S	I CRIT=__DEG
24	Displays critical I		R/S	BETA =___DEG

25	Displays failure plane angle, BETA		R/S	DWCRIT=___FT
26	Displays critical DW		R/S	DZCRIT=___FT
27	Displays critical DZ		R/S	BW =___FT
28	Displays failure block width, BW		R/S	VB =___FT3/FT
29	Displays failure block volume per unit channel length, VB		R/S	INITIAL FAILURE COMPLETE FOR NEW BANK PRESS: 0 R/S FOR SUBSEQUENT FAILURES PRESS: 1 R/S
30	Input code: 0 = go to step 1 1 = to continue	0 or 1	R/S	ANALYSIS OF SUBSEQUENT FAILURES STEP NO.___.
31	Initiates program for subsequent failures		R/S	FSS =___
32	Displays factor of safety for bank after initial failure		R/S	BANK STABLE
33	Indicates that new geometry is stable. No failure will occur without erosion and/or degradation		R/S	STEP NO.__.
34	Displays number of current step		R/S	DW ? FT
35	Input lateral erosion distance	DW	R/S	DZ ? FT
36	Input degradation depth	DZ	R/S	H=___FT
37	Displays new H		R/S	HI=___FT
38	Displays new H1		R/S	I =___DEG
39	Displays new I		R/S	FSS=___

40	Displays new FSS		R/S	A: BANK STABLE B: H = CRITICAL C: BANK TOO STEEP
41	Displays A,B, or C If A, go to step 33 If B, go to step 43 If C, continue			
	Indicates DW &/or DZ were too large so bank geometry is unstable and could not exist		R/S	REDUCE DW +DZ
42	Indicates reduced DW &/or DZ values must be used and step repeated		R/S	STEP NO.__.
43	Indicates bank is on point of failure		R/S	H CRIT=___FT
44	Displays critical H		R/S	H1CRIT=___FT
45	Displays critical H1		R/S	Y CRIT=___FT
46	Displays critical Y		R/S	BETA =___DEG
47	Displays failure plane angle, BETA		R/S	DWCRIT =___FT
48	Displays critical DW		R/S	DZCRIT =___FT
49	Displays critical DZ		R/S	BW =___FT
50	Displays failure block width, BW		R/S	VB =___FT3/FT
51	Displays failure block volume per unit channel length, VB		R/S	RUN COMPLETE FOR NEW BANK PRESS: 0 R/S FOR NEXT FAILURE PRESS: 1 R/S
52	Input code: 0 = go to step 1 1 = go to step 30	0 or 1	R/S	

Table 2 Results Table

Stream Name	Site Name
Date	Bank (L or R)

Initial Data

Bank Geometry Data	H = ft	H1 = ft I = deg	K =
Bank Material Data	Sp.Wt = lb/ft³	phi = deg c = lb/ft²	

Initial Failure

Step	DW (ft)	DZ (ft)	H (ft)	H1 (ft)	I (deg)	FS (—)	COMMENTS

Critical Bank Geometry Parameters for Initial Failure

H_{CRIT} = ft	$H1_{CRIT}$ = ft	Y_{CRIT} = ft	I_{CRIT} = deg	BETA = deg
DW_{CRIT} = ft	DZ_{CRIT} = ft	BW = ft	VB = ft³/ft	

Subsequent Failures

Step	DW (ft)	DZ (ft)	H (ft)	H1 (ft)	I (deg)	FSS (—)	COMMENTS

Critical Parameters for Subsequent Bank Failures

H_{CRIT} = ft	$H1_{CRIT}$ = ft	Y_{CRIT} = ft	BETA = deg
DW_{CRIT} = ft	DZ_{CRIT} = ft	BW = ft	VB = ft³/ft

4.2 Flow Charts

The flow charts for the programs for initial and subsequent failures are shown in Figs. 4 and 5, respectively.

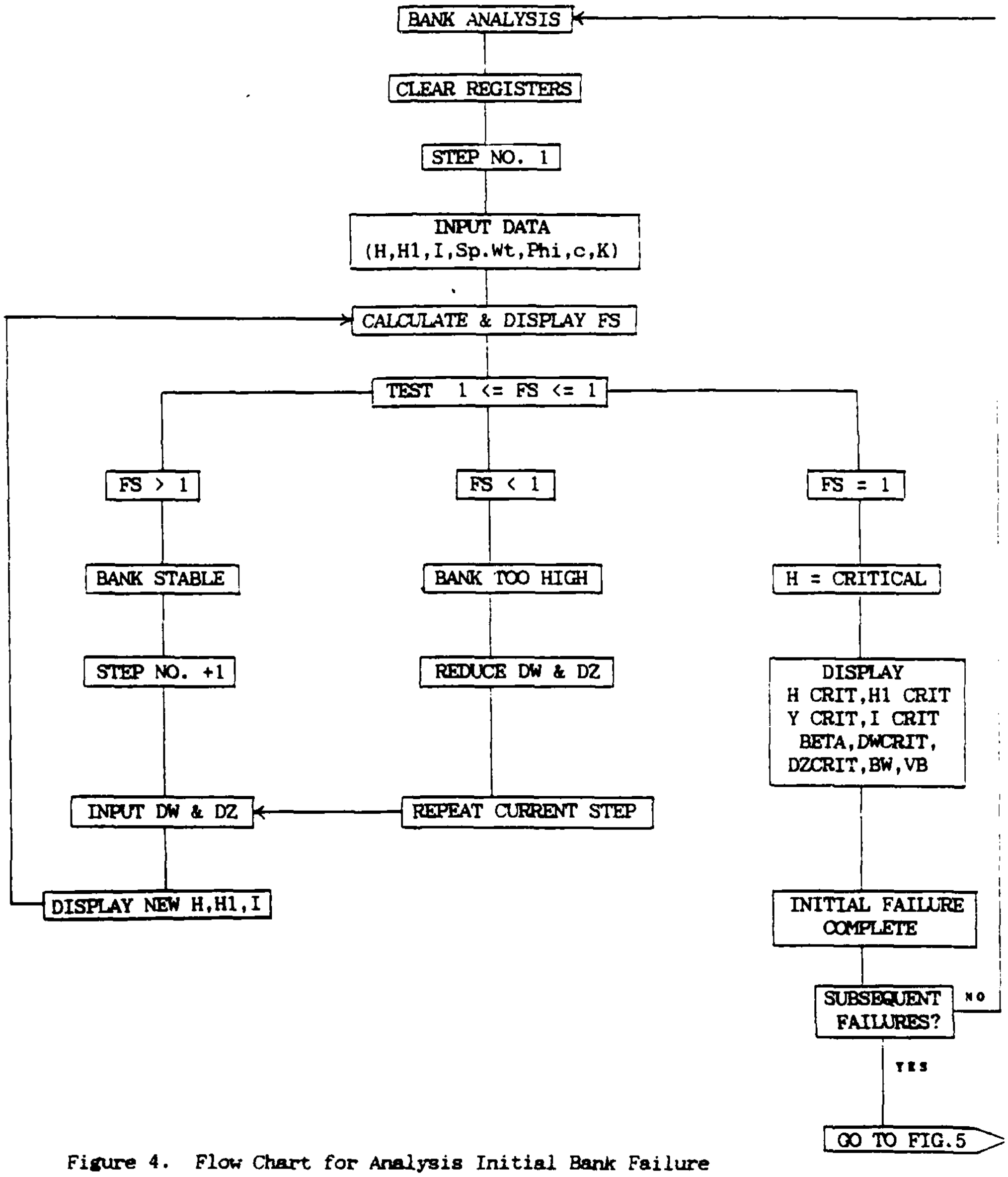

Figure 4. Flow Chart for Analysis Initial Bank Failure

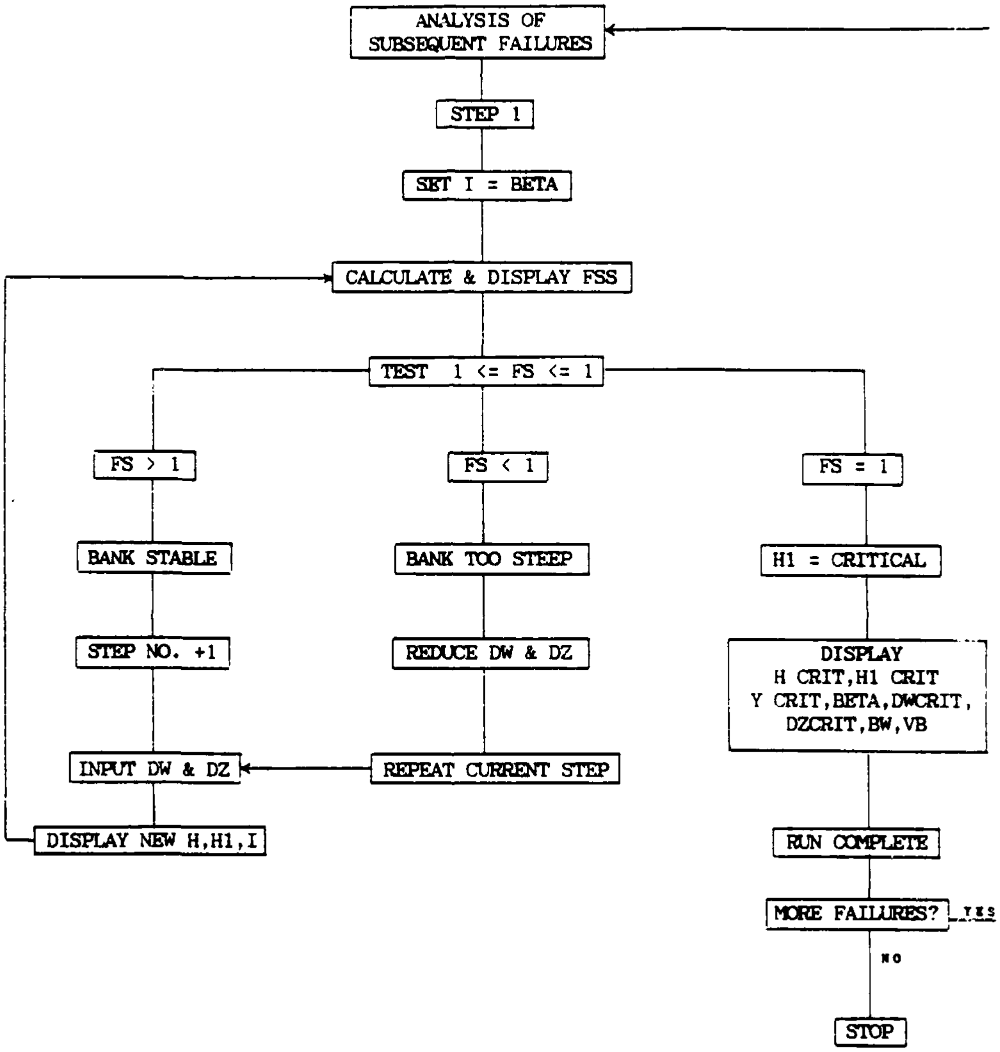

Figure 5. Flow Chart for Analysis of Subsequent Failures

4.3 Errors and Warning Messages

Keying and data errors may halt the program and produce error messages. Standard error messages are explained in the HP users manual, but additional messages associated with with these programs are listed and explained in Appendix 2. Under some circumstances warning messages that do not halt the program are displayed. These are also listed in Appendix 2.

5 EXAMPLE

5.1 Background

In this section a worked example is presented to illustrate the use of the program. The parameters used apply to no particular stream, but are not atypical of a degrading river with alluvial bank materials. Firstly, the steps and keystrokes to run the program are set out. Secondly, the completed table of results is presented. Thirdly, the results are discussed and interpreted briefly.

5.2 Program Steps: Initial Failure

****

KEYSTROKE	DISPLAY
XEQ ALPHA USFS ALPHA	COLIN THORNE- BANK ANALYSIS STEP NO. 1. H? FT
15 R/S	H1? FT
15 R/S	I? DEG
70 R/S	SP.WT? LB/FT3
100 R/S	PHI? DEG
12 R/S	C? LB/FT2
400 R/S	K?
0.5 R/S	FS = 1.30
R/S	BANK STABLE
R/S	STEP NO. 2.
R/S	DW? FT
0.6 R/S	DZ? FT
1.5 R/S	H = 16.50 FT
R/S	H1 = 13.35 FT
R/S	I = 70 DEG
R/S	FS = 1.11
R/S	BANK STABLE
R/S	STEP NO. 3.
R/S	DW? FT
0.6 R/S	DZ? FT
1.2 R/S	H = 17.70 FT
R/S	H1 = 11.70 FT
R/S	I = 70 DEG
R/S	FS = 0.98
R/S	BANK TOO HIGH
R/S	REDUCE DW + DZ
R/S	STEP NO. 3.
R/S	DW? FT
0.5 R/S	DZ? FT
1.1 R/S	H = 17.60 FT
R/S	H1 = 11.98 FT
R/S	I = 70 DEG
R/S	FS = 1.00
R/S	H = CRITICAL
R/S	H CRIT = 17.6FT
R/S	H1CRIT = 12.0FT
R/S	Y CRIT = 8.8 FT
R/S	I CRIT = 70 DEG

R/S	BETA = 44.7 DEG
R/S	DWCRIT = 1.1 FT
R/S	DZCRIT = 2.6 FT
R/S	BW = 4.54 FT
R/S	VB = 91.4FT3/FT
R/S	1ST FAILURE COMPLETE FOR NEW BANK PRESS: 0 R/S TO CONTINUE PRESS: 1 R/S

5.3 Program Steps: Subsequent Failures

KEYSTROKE	DISPLAY
1 R/S	ANALYSIS OF SUBSEQUENT FAILURES STEP NO. 4.
R/S	H = 17.60FT
R/S	H1 = 17.60FT
R/S	I = 44.7DEG
R/S	FSS = 1.33
R/S	BANK STABLE
R/S	STEP NO. 2.
R/S	DW ? FT
5 R/S	DZ ? FT
0 R/S	H = 17.60FT
R/S	H1 = 12.66FT
R/S	I = 44.7DEG
R/S	FSS= 1.07
R/S	BANK STABLE
R/S	STEP NO. 5.
R/S	DW ? FT
1.5 R/S	DZ ? FT
0.0 R/S	H = 17.60FT
R/S	H1 = 11.18FT
R/S	I = 44.7DEG
R/S	FSS= 0.99
R/S	BANK TOO STEEP
R/S	REDUCE DW + DZ
R/S	STEP NO. 6.
R/S	DW ? FT
1.2 R/S	DZ ? FT
0.0 R/S	H = 17.60FT
R/S	H1 = 11.48FT
R/S	I = 44.7DEG
R/S	FSS= 1.00
R/S	H1 = CRITICAL
R/S	H CRIT = 17.6FT
R/S	H1CRIT = 11.5FT
R/S	Y CRIT = 8.8 FT
R/S	BETA = 44.7 DEG
R/S	DWCRIT = 6.2 FT

R/S	DZCRIT = 0.0 FT
R/S	BW = 6.20 FT
R/S	VB = 90.1FT3/FT
R/S	RUN COMPLETE
	FOR NEW BANK
	PRESS: 0 R/S
	TO CONTINUE
	PRESS: 1 R/S
0 R/S	COLIN THORNE-
	BANK STABILITY
	STEP NO. 1.
	H ? FT

****

5.4 Results

The results table for this example is shown in Table 3. In step 1 the initia configuration of the bank is found to have a factor of safety, FS = 1.3, indicatin that it is stable (Fig.6a). Mass failure is therefore unlikely to occur unles fluvial processes of lateral erosion and bed degradation increase the bank height an angle significantly. In step 2, 0.6ft of erosion and 1.5ft of degradation is seen t reduce FS to 1.11. The bank is still stable (Fig.6b). In step 3, the bank's respons to a further 0.6ft of erosion and 1.2ft of degradation is examined and it is foun that FS = 0.98, that is the bank is unstable and should already have failed. Repeating step 3 with slightly reduced erosion (0.5ft) and degradation (1.1ft) amount identifies the critical condition for slab failure (Fig.6c).

Step 1 of the analysis of subsequent failures shows that after the initia failure, the bank is again stable (Fig.6d). The flow now cleans out the disturbe bank material from the initial failure and recommences to erode the bank laterally. Further degradation of the bed is unlikely at this stage because of the copious suppl of sediment to the channel from mass failures of the banks once they reach th critical height. In step 2, 5ft of lateral erosion of the lower bank has reduced th factor of safety with respect to subsequent failures, FSS to 1.07, but the bank i just still stable (Fig.6e). Step 3 inputs a further 1.5ft of erosion, but this is a little too much as FSS drops below unity to 0.99. Repeating step 3 with 1.2ft o lateral erosion identifies the critical condition with FSS = 1.00 (Fig.6f).

Further subsequent failures simply repeat the sequence of events: Slab failure: basal clean-out; lateral erosion; slab failure, and the bank retreats by paralle retreat at a rate controlled by the ability of the flow to clean-out the slough debri and re-erode the bank to a critical condition (Thorne and Osman, 1988).

6 AKNOWLEDGEMENTS

The program described here was developed while the author was a visitin scientist at the US Army Corps of Enginneers, Waterways Experiment Station. The hel and advice of Dr Bob Brown and John Ingram at WES is gratefully acknowledged. Th program was developed for use by the Lower Mississippi, Vicksburg District, Corps o Engineers, as part of a study of streambank stability in the DEC watersheds. Phi combs and David Biedenharn at the District provided support, advice and data for th development of the program. The work was funded by the Vicksburg District,through WE and the US Army European Research Office.

Table 3 Example Results Table

Stream Name	Nowhere Creek	Site	Name No Place
Date	10/20/87	Bank	Left

Initial Data

Bank Geometry Data	H = 15.0 ft	H1 = 15.0 ft	I = 70.0 deg	K = 0.5
Bank Material Data	Sp.Wt = 100 lb/ft^3	phi = 12.0 deg	c = 400 lb/ft^2	

Initial Failure

Step	DW (ft)	DZ (ft)	H (ft)	H1 (ft)	I (deg)	FS (--)	COMMENTS
1	0	0	15.00	15.00	70	1.30	Stable
2	0.6	1.5	16.50	13.35	70	1.11	Stable
3	0.6	1.2	17.70	11.70	70	0.98	Too High
3	0.5	1.1	17.60	11.98	70	1.00	Critical

Critical Bank Geometry Parameters for Initial Failure

H_{CRIT} = 17.6 ft	$H1_{CRIT}$ = 12 ft	Y_{CRIT} = 8.8 ft	I_{CRIT} = 70.0 deg	BETA = 44.7 deg
DW_{CRIT} = 1.1 ft	DZ_{CRIT} = 2.6 ft	BW = 4.54 ft	VB = 91.4 ft^3/ft	

Subsequent Failures

Step	DW (ft)	DZ (ft)	H (ft)	H1 (ft)	I (deg)	FSS (--)	COMMENTS
4	0	0	17.60	17.60	44.7	1.33	Stable
5	5.0	0	17.60	12.60	44.7	1.07	Stable
6	1.5	0	17.60	11.18	44.7	0.99	Too Steep
6	1.2	0	17.60	11.48	44.7	1.00	Critical

Critical Parameters for Subsequent Bank Failures

H_{CRIT} = 17.6 ft	$H1_{CRIT}$ = 11.5 ft	Y_{CRIT} = 8.8 ft	BETA = 44.7 deg
DW_{CRIT} = 6.2 ft	DZ_{CRIT} = --- ft	BW = 6.2 ft	VB = 90.1 ft^3/ft

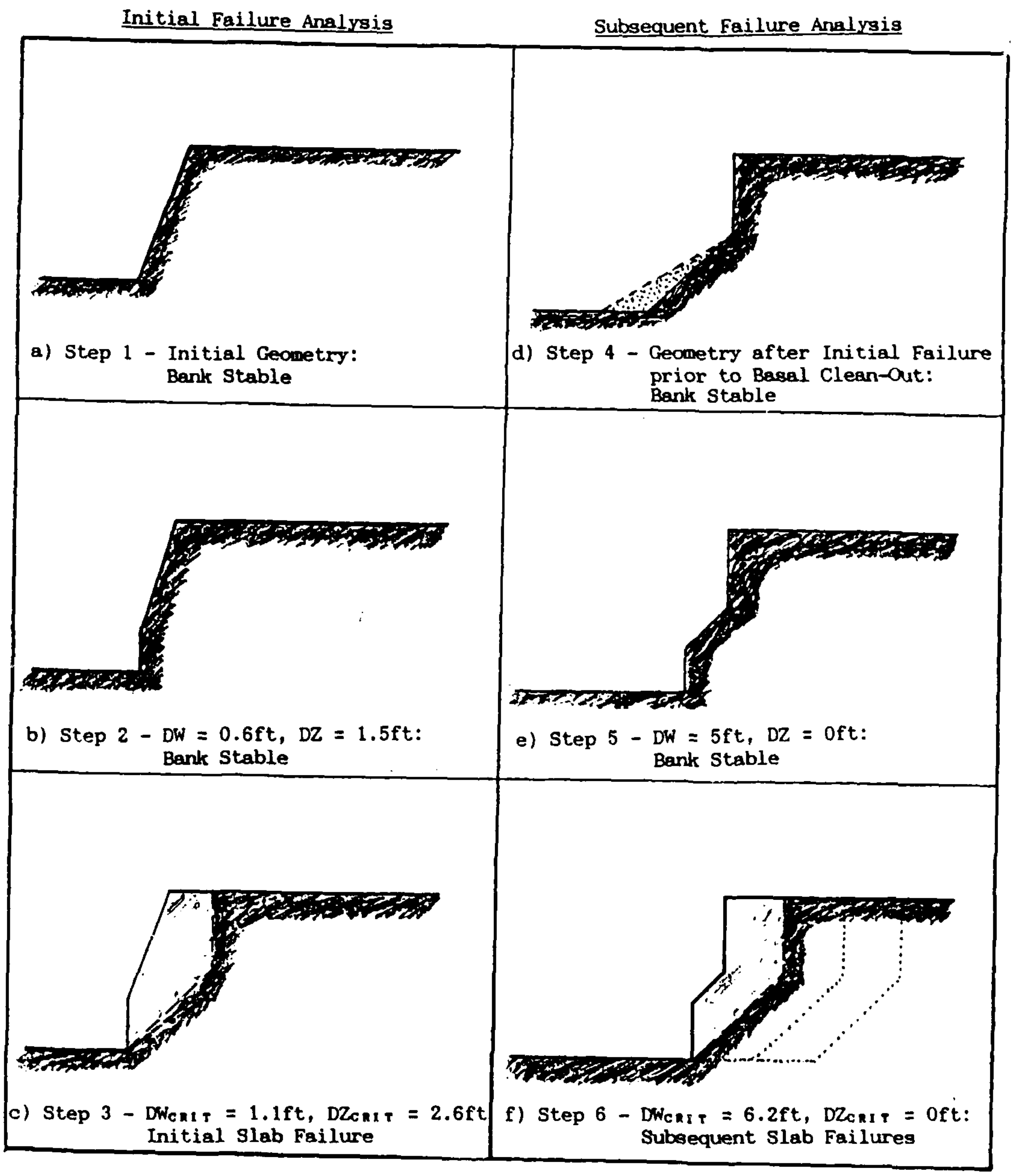

Figure 6. Stages of Bank Erosion, Failure and Retreat in Worked Example

7 REFERENCES

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8 LIST OF SYMBOLS

BETA	Angle between the failure plane and the horizontal. Becomes the new bank angle after initial slab failure.
c	Effective cohesion of bank material.
DW	Increment of lateral bank erosion by the flow.
DW_{CRIT}	Critical lateral erosion distance for slab failure.
DZ	Increment of bed degradation by the flow.
DZ_{CRIT}	Critical degradation depth for slab failure.
FS	Factor of safety with respect to initial slab failure.
FSS	Factor of safety with respect to subsequent slab failures.
H	Total bank height above the bed.
H_{CRIT}	Critical total bank height for slab failure.
H1	Upper bank height. Equals total bank height if DW and DZ are zero. Equals total bank height if bank is vertical.
$H1_{CRIT}$	Critical upper bank height for slab failure.
I	Angle between the bank surface and the horizontal.
I_{CRIT}	Bank angle at slab failure.
K	Tension crack index. K = Y/H.
phi	Effective angle of internal friction of bank material.
Sp.Wt	Specific weight of bank material.
VB	Volume of failure block per unit channel length.
Y	Depth of tension cracking.
Y_{CRIT}	Tension crack depth at slab failure.

APPENDIX 1 - PROGRAM LISTING

INITIAL FAILURE ANALYSIS

```
01♦LBL "USFS"
02 CLX
03 "COLINTHORNE-"
04 AVIEW
05 PSE
06 "BANKANALYSIS"
07 AVIEW
08 PSE
09 CLRG
10♦LBL 01
11 1
12 STO 24
13 FIX 0
14 "STEP NO."
15 ARCL 24
16 AVIEW
17 PSE
18 "H? FT"
19 PROMPT
20 STO 01
21 "H1? FT"
22 PROMPT
23 STO 02
24 RCL 01
25 /
26 1/X
27 1
28 X<=Y?
29 GTO 02
30 TONE 1
31 "H1>H,BAD DATA"
32 PROMPT
33 ST- 24
34 GTO 01
35♦LBL 02
36 "I? DEG"
37 PROMPT
38 STO 03
39 60
40 X<=Y?
41 GTO 03
42 TONE 9
43 "WARNING: I<60"
44 AVIEW
45 PSE
46♦LBL 03
47 90
48 RCL 03
49 X<=Y?
50 GTO 04
51 TONE 1
52 "I>90,BAD DATA"
53 PROMPT
54 GTO 02
55♦LBL 04
56 "SP.WT? LB/FT3"
57 PROMPT
58 STO 04
59 "PHI? DEG"
60 PROMPT
61 STO 05
62 "C? LB/FT2"
63 PROMPT
64 STO 06
65♦LBL 05
66 "K?"
67 PROMPT
68 STO 07
69 1
70 X>Y?
71 GTO 06
72 TONE 1
73 "K>1, BAD DATA"
74 PROMPT
75 GTO 05
76♦LBL 06
77 RCL 01
78 RCL 02
79 /
80 STO 20
81 0
82 X>Y?
83 GTO 07
84 RCL 03
85 TAN
86 1
87 RCL 07
88 X↑2
89 -
90 *
91 RCL 01
92 RCL 02
93 /
94 X↑2
95 *
96 ATAN
97 RCL 05
98 +
99 2
100 /
101 STO 08
102 1
103 RCL 07
104 X↑2
105 -
106 RCL 08
107 SIN
108 RCL 08
109 COS
110 *
111 RCL 08
112 COS
113 X↑2
114 RCL 05
115 TAN
116 *
117 -
118 *
119 STO 09
120 2
121 ENTER↑
122 1
123 RCL 07
124 -
125 *
126 RCL 06
127 *
128 RCL 04
129 /
130 RCL 02
131 /
132 STO 10
133 RCL 08
134 SIN
135 RCL 08
136 COS
137 *
138 RCL 05
139 TAN
140 *
141 RCL 08
142 SIN
143 X↑2
144 -
145 RCL 03
146 TAN
147 /
148 STO 11
149 RCL 10
150 RCL 09
151 /
152 STO 12
153 X↑2
154 4
155 RCL 11
156 *
157 RCL 09
158 /
159 -
160 SQRT
161 RCL 12
162 +
163 2
164 /
165 STO 13
166 RCL 13
167 RCL 20
168 /
169 STO 25
170 FIX 2
171 "FS="
172 ARCL 25
173 PROMPT
174 1.005
175 X<=Y?
176 GTO 08
177 RCL 25
178 .995
179 X>Y?
180 GTO 07
181 BEEP
182 "H=CRITICAL"
183 PROMPT
184 FIX 1
185 "H CRIT="
186 ARCL 01
187 "├FT"
188 PROMPT
189 "H1CRIT="
190 ARCL 02
191 "├FT"
192 PROMPT
193 RCL 01
194 RCL 07
195 *
196 STO 28
197 "Y CRIT="
198 ARCL 28
199 "├FT"
200 PROMPT
201 "ICRIT="
202 ARCL 03
203 "├DEG"
204 PROMPT
205 "BETA="
206 ARCL 08
207 "├ DEG"
208 PROMPT
209 "DWCRIT="
210 ARCL 17
211 "├FT"
212 PROMPT
213 "DZCRIT="
214 ARCL 18
215 "├FT"
216 PROMPT
```

```
217 RCL 01
218 RCL 01
219 RCL 07
220 *
221 -
222 RCL 08
223 TAN
224 /
225 RCL 02
226 RCL 03
227 TAN
228 /
229 -
230 STO 26
231 FIX 2
232 "BW="
233 ARCL 26
234 "⊢ FT"
235 PROMPT
236 RCL 01
237 X↑2
238 RCL 01
239 RCL 07
240 *
241 X↑2
242 -
243 RCL 08
244 TAN
245 /
246 RCL 02
247 X↑2
248 RCL 03
249 TAN
250 /
251 -
252 2
253 /
254 STO 27
255 FIX 1
256 "VB="
257 ARCL 27
258 "⊢FT3/FT"
259 PROMPT
260 1
261 "1ST FAILURE"
262 AVIEW
263 PSE
264 "COMPLETE"
265 AVIEW
266 PSE
267 "FOR NEW BANK"
268 AVIEW
269 PSE
270 "PRESS: 0 R/S"
271 AVIEW
272 PSE
273 "FOR"
274 AVIEW
275 PSE
276 "SUBSEQUENT"
277 AVIEW
278 PSE
279 "FAILURES"
280 AVIEW
281 PSE
282 "PRESS: 1 R/S"
283 PROMPT
284 X=Y?
285 "I"
286 GTO "FSS"
287 GTO "USFS"
288♦LBL 08
289 "BANK STABLE"
290 PROMPT
291♦LBL 09
292 1
293 ST+ 24
294 FIX 0
295 "STEP NO. "
296 ARCL 24
297 PROMPT
298 RCL 03
299 90
300 X=Y?
301 GTO 10
302 RCL 20
303 10
304 X<=Y?
305 GTO 11
306 "DW? FT"
307 PROMPT
308 ST+ 17
309 STO 21
310 RCL 02
311 RCL 21
312 RCL 03
313 TAN
314 *
315 STO 16
316 X=0?
317 GTO 10
318 /
319 STO 23
320 1.005
321 X<=Y?
322 GTO 12
323 RCL 23
324 .995
325 X<=Y?
326 GTO 11
327 TONE 9
328 "H1<0,REDUCEDW"
329 PROMPT
330 1
331 ST- 24
332 RCL 21
333 ST- 17
334 GTO 09
335♦LBL 12
336 RCL 02
337 RCL 16
338 -
339 STO 02
340 GTO 10
341♦LBL 11
342 CLX
343 STO 21
344 90
345 STO 03
346 TONE 5
347 "BANKVERTICAL"
348 AVIEW
349 PSE
350 "DUETOEROSION"
351 AVIEW
352 PSE
353♦LBL 10
354 CLX
355 "DZ? FT"
356 PROMPT
357 STO 22
358 ST+ 18
359 RCL 01
360 +
361 STO 01
362 FIX 2
363 "H="
364 ARCL 01
365 "⊢ FT"
366 PROMPT
367 90
368 RCL 03
369 X=Y?
370 GTO 13
371♦LBL 14
372 "H1="
373 ARCL 02
374 "⊢ FT"
375 PROMPT
376 FIX 1
377 "I= "
378 ARCL 03
379 "⊢ DEG"
380 PROMPT
381 GTO 06
382♦LBL 13
383 RCL 01
384 STO 02
385 GTO 14
386♦LBL 07
387 1
388 ST- 24
389 RCL 24
390 X=0?
391 GTO 15
392 TONE 5
393 "BANKTOO HIGH"
394 PROMPT
395 "REDUCE DW+DZ"
396 PROMPT
397 RCL 01
398 RCL 22
399 -
400 STO 01
401 RCL 22
402 ST- 18
403 90
404 RCL 03
405 X=Y?
406 GTO 16
407 TAN
408 RCL 21
409 *
410 RCL 02
411 +
412 STO 02
413 RCL 21
414 ST- 17
415 GTO 09
416♦LBL 16
417 RCL 01
418 STO 02
419 GTO 09
420♦LBL 15
421 TONE 3
422 TONE 1
423 "BANK:UNSTABLE"
424 AVIEW
425 PSE
426 "CHECK DATA"
427 AVIEW
428 PSE
429 1
430 ST- 24
431 GTO 01
432 END
```

SUSEQUENT FAILURE ANALYSIS

```
01♦LBL "FSS"
02 "ANALYSIS OF"
03 AVIEW
04 PSE
05 "SUBSEQUENT"
06 AVIEW
07 PSE
08 "FAILURES"
09 AVIEW
10 PSE
11 1
12 ST+ 24
13 FIX 0
14 "STEP NO. "
15 ARCL 24
16 PROMPT
17 RCL 01
18 STO 02
19 RCL 08
20 STO 03
21 0
22 STO 17
23 STO 18
24♦LBL 17
25 RCL 01
26 RCL 02
27 /
28 STO 20
29 RCL 08
30 COS
31 RCL 08
32 SIN
33 *
34 RCL 08
35 COS
36 X↑2
37 RCL 05
38 TAN
39 *
40 -
41 STO 14
42 2
43 ENTER↑
44 1
45 RCL 07
46 -
47 *
48 RCL 06
49 *
50 RCL 04
51 /
52 RCL 02
53 /
54 STO 15
55 RCL 14
56 /
57 X↑2
58 4
59 +
60 SQRT
61 RCL 15
62 RCL 14
63 /
64 +
65 2
66 /
67 STO 13
68 RCL 20
69 /
70 STO 25
71 FIX 2
72 "FSS="
73 ARCL 25
74 PROMPT
75 1.005
76 X<=Y?
77 GTO 18
78 RCL 25
79 .995
80 X>Y?
81 GTO 19
82 BEEP
83 "H1=CRITICAL"
84 PROMPT
85 FIX 1
86 "H CRIT="
87 ARCL 01
88 "⊢FT"
89 PROMPT
90 "H1CRIT="
91 ARCL 02
92 "⊢FT"
93 PROMPT
94 RCL 01
95 RCL 07
96 *
97 STO 28
98 "Y CRIT="
99 ARCL 28
100 "⊢FT"
101 PROMPT
102 "BETA="
103 ARCL 08
104 "⊢DEG"
105 PROMPT
106 "DWCRIT="
107 ARCL 17
108 "⊢FT"
109 PROMPT
110 "DZCRIT="
111 ARCL 18
112 "⊢FT"
113 PROMPT
114 RCL 01
115 RCL 02
116 -
117 RCL 08
118 TAN
119 /
120 STO 30
121 FIX 2
122 "BW="
123 ARCL 30
124 "⊢FT"
125 PROMPT
126 RCL 01
127 X↑2
128 RCL 02
129 X↑2
130 -
131 2
132 /
133 RCL 08
134 TAN
135 /
136 STO 31
137 FIX 1
138 "VB="
139 ARCL 31
140 "⊢FT3/FT"
141 PROMPT
142 "RUN COMPLETE"
143 AVIEW
144 PSE
145 1
146 ENTER↑
147 "FOR NEW BANK"
148 AVIEW
149 PSE
150 "PRESS: 0 R/S"
151 AVIEW
152 PSE
153 "TO CONTINUE"
154 AVIEW
155 PSE
156 "PRESS: 1 R/S"
157 PROMPT
158 X=Y?
159 GTO "FSS"
160 GTO "USFS"
```

```
161♦LBL 18
162 "BANK STABLE"
163 PROMPT
164♦LBL 20
165 1
166 ST+ 24
167 FIX 0
168 "STEP NO. "
169 ARCL 24
170 PROMPT
171 "DW? FT"
172 PROMPT
173 STO 21
174 ST+ 17
175♦LBL 21
176 RCL 21
177 RCL 08
178 TAN
179 *
180 STO 16
181 CHS
182 RCL 02
183 +
184 STO 02
185♦LBL 22
186 CLX
187 "DZ? FT"
188 PROMPT
189 STO 22
190 ST+ 18
191 RCL 01
192 +
193 STO 01
194 FIX 2
195 "H="
196 ARCL 01
197 "├FT"
198 PROMPT
199♦LBL 24
200 "H1="
201 ARCL 02
202 "├FT"
203 PROMPT
204 "I= "
205 ARCL 03
206 "├ DEG"
207 PROMPT
208 GTO 17
209♦LBL 19
210 1
211 ST- 24
212 TONE 5
213 "BANKTOOSTEEP"
214 PROMPT
215 "REDUCE DW+DZ"
216 PROMPT
217♦LBL 25
218 RCL 01
219 RCL 22
220 ST- 18
221 -
222 STO 01
223 RCL 16
224 RCL 02
225 +
226 STO 02
227 RCL 21
228 ST- 17
229 GTO 20
230 .END.
```

APPENDIX 2 - MESSAGES AND ERRORS

DISPLAY	MEANING
BANK UNSTABLE : CHECK DATA	The initial bank geometry has a factor of safety less than 1. If "worst case" values are being used then this means that the bank is at risk of failure. If "average" values are being used then input data are suspect and should be checked. Keying R/S returns the program to Step 1.
BANK VERTICAL DUE TO EROSION	Lateral erosion reduces the height of the upper bank, H1. If H1 goes to zero before failure, the sloping portion of the bank is eliminated and the bank is made vertical. In this case the program makes I = 90° and H1 = H. Further lateral erosion produces retreat of the whole bank, but does not affect mass stability. Therefore, no further DW values are requested. Vertical banks may fail due to bed degradation, represented by further DZ increments. If further lateral erosion produces an overhanging bank, this can be analysed using the Thorne-Tovey (1981) analysis.
H1>H BAD DATA	The upper bank height input is greater than the total bank height, which is impossible. Program will not accept H1>H. If initial DW & DZ are zero, then H1 = H. Keying R/S returns the program to Step 1.
H1<0, REDUCE DW	The input value of DW would reduce H1 below zero which is impossible. H<=H1>0 by definition. If H1 goes to zero then the whole bank is vertical and H = H1. This is taken into account in the program when the message 'BANK VERTICAL DUE TO EROSION' is displayed. Keying R/S returns the program to Step 12 and prompts for a reduced DW value.
I>90, BAD DATA	Input value of the bank angle I is greater than 90°, inferring either a data error or a cantilevered bank. Cantilever stability can be assessed using the Thorne-Tovey (1981) analysis. The slab analysis used here would be inapplicable. Keying R/S returns the program to Step 6 and prompts for another value of I.
K>1 BAD DATA	Input value of tension crack index K is greater than 1, which is impossible. Check value of K. Keying R/S returns the program to Step 8 and prompts for another value of K.
WARNING : I<60	Input value of bank angle I is less 60°. Such banks often fail by rotational slip, not slab failure and this analysis may significantly *overestimate* the factor of safety. Program continues, but results should be used with *caution* for I<60 degrees.

APPENDIX B

STABILITY CHARTS FOR ROTATIONAL SLIP FAILURE OF ERODING RIVERBANKS

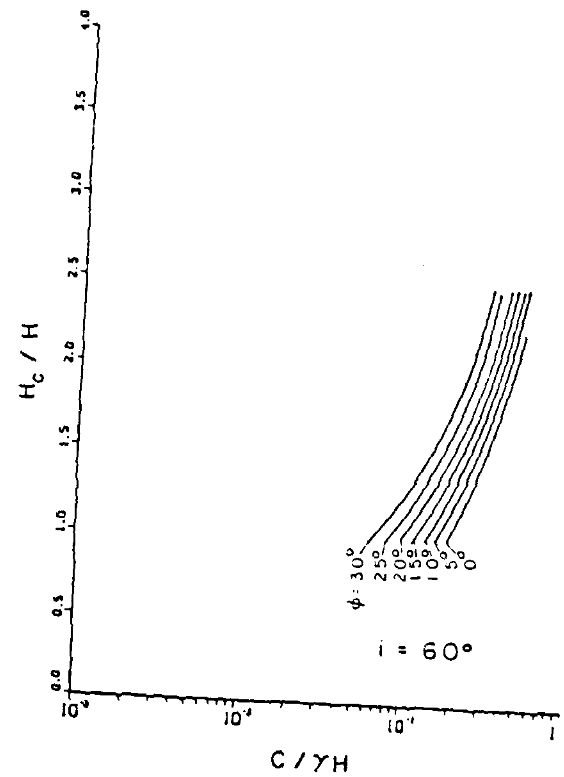

Figure 3.6. Stability charts of gentle slopes.

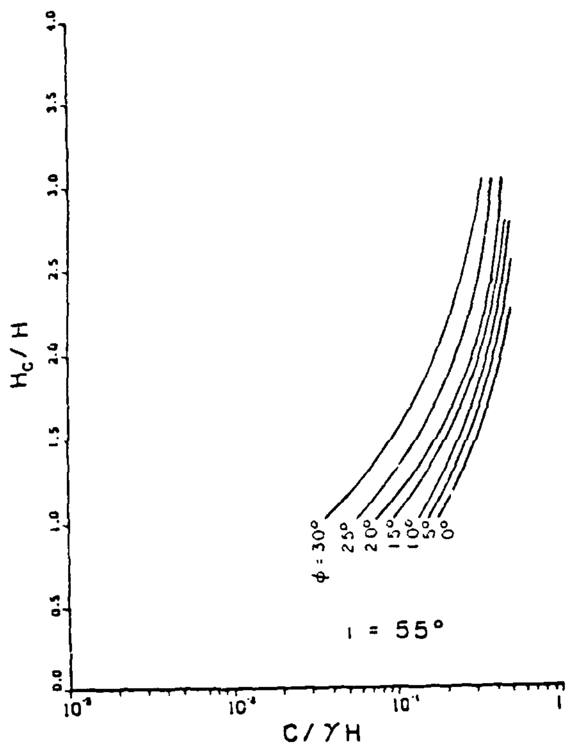

Figure 3.7. Stability charts of gentle slopes.

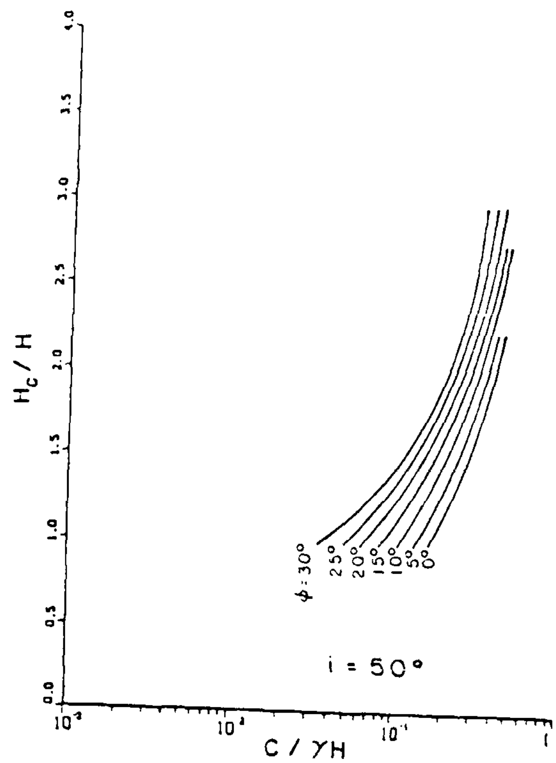

Figure 3.8. Stability charts of gentle slopes.

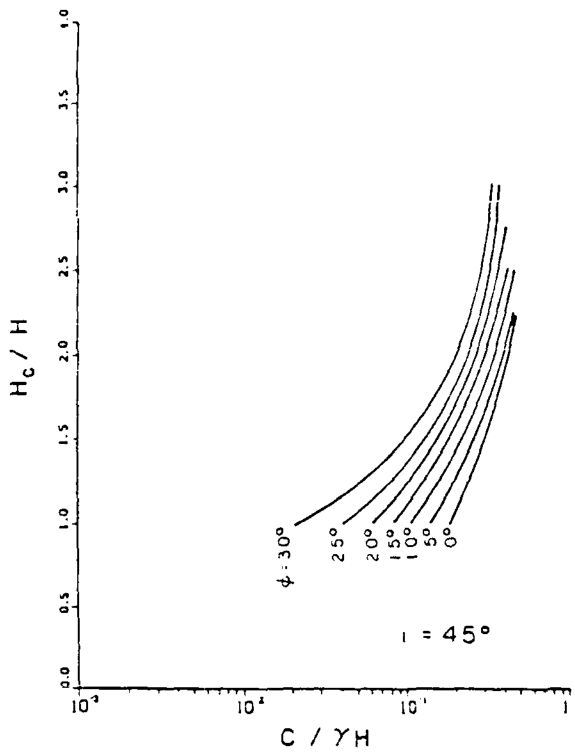

Figure 3.9. Stability charts of gentle slopes.

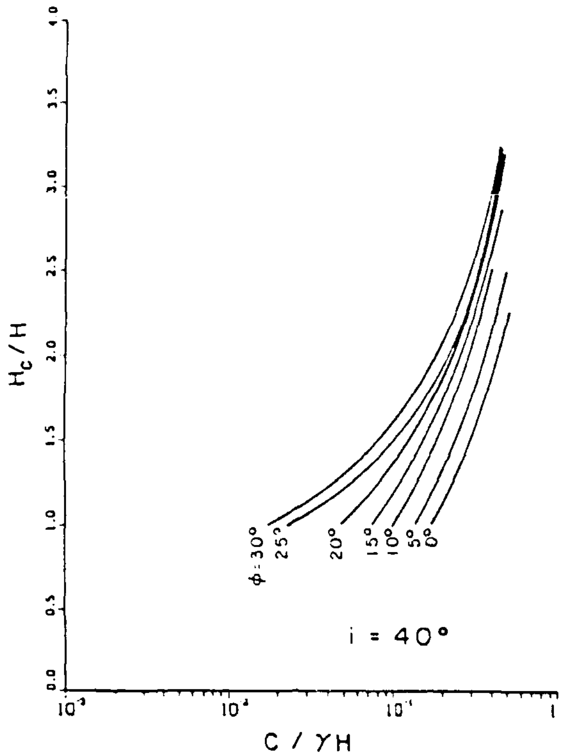

Figure 3.10. Stability charts of gentle slopes.

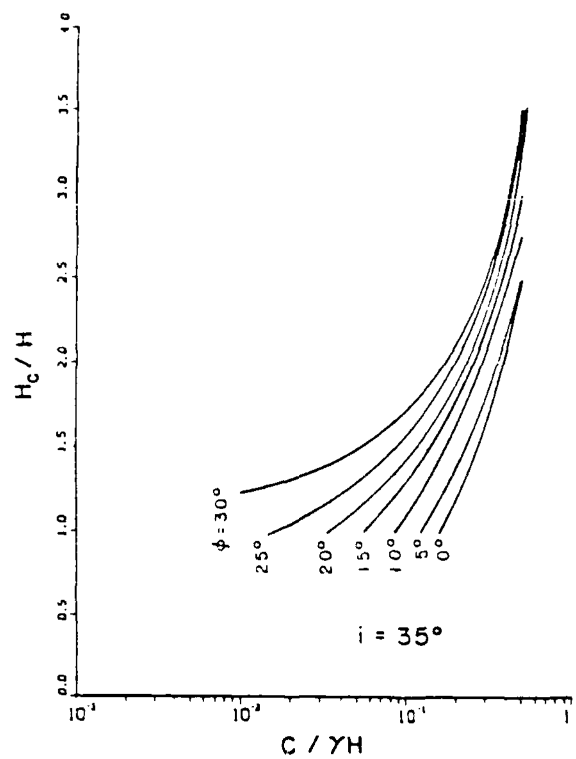

Figure 3.11. Stability charts of gentle slopes.

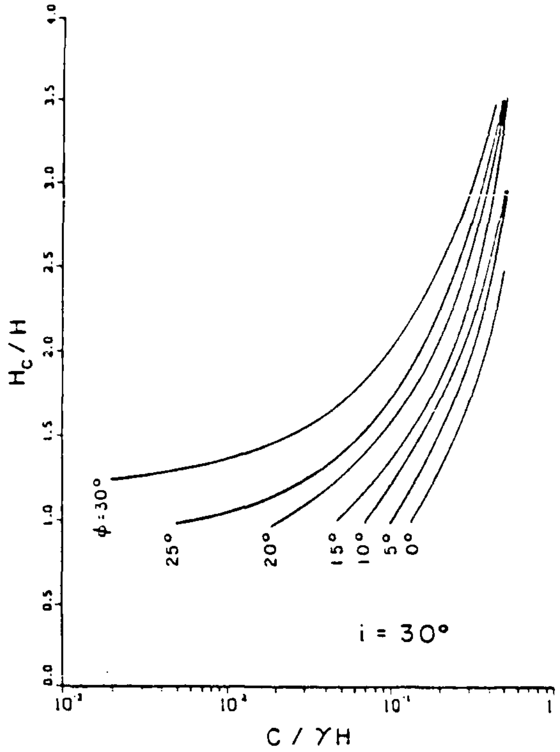

Figure 3.12. Stability charts of gentle slopes.

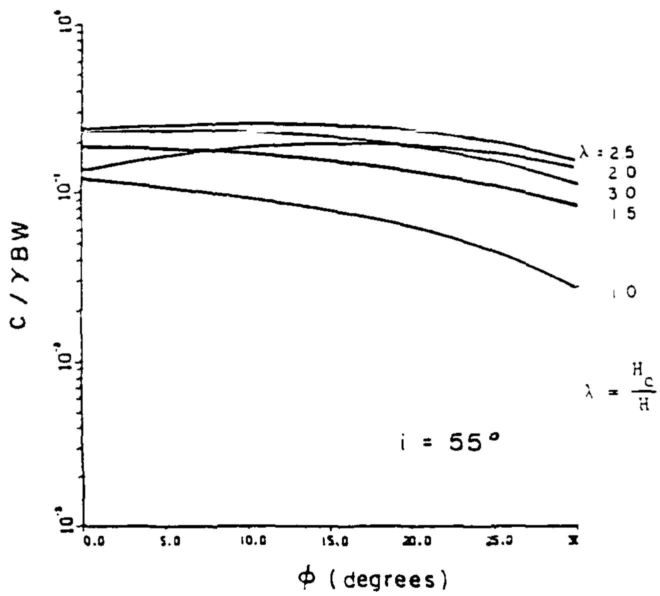

Figure 3.13. Estimation of failure block width (gentle slope).

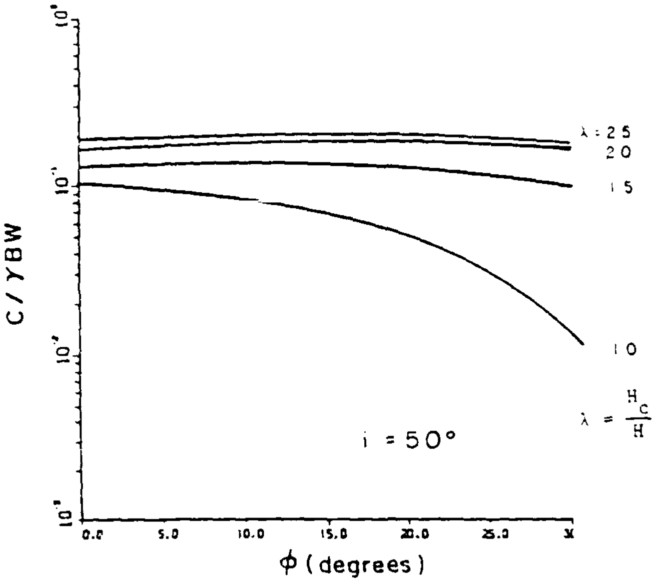

Figure 3.14. Estimation of failure block width (gentle slope).

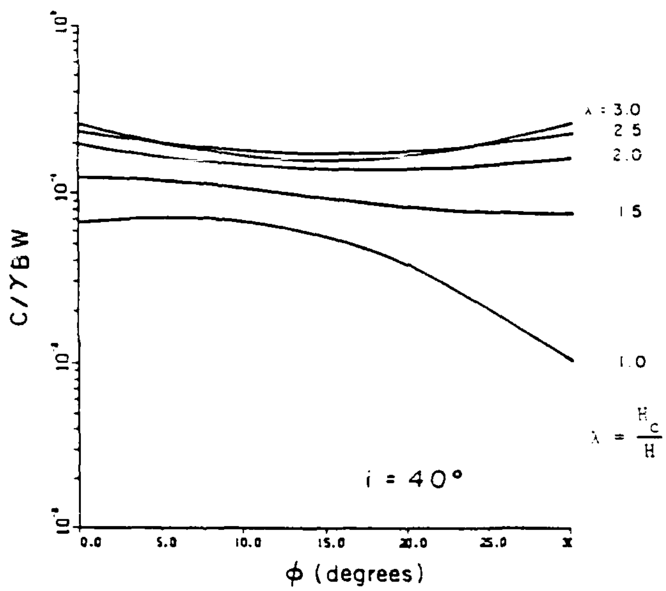

Figure 3.15. Estimation of failure block width (gentle slope).

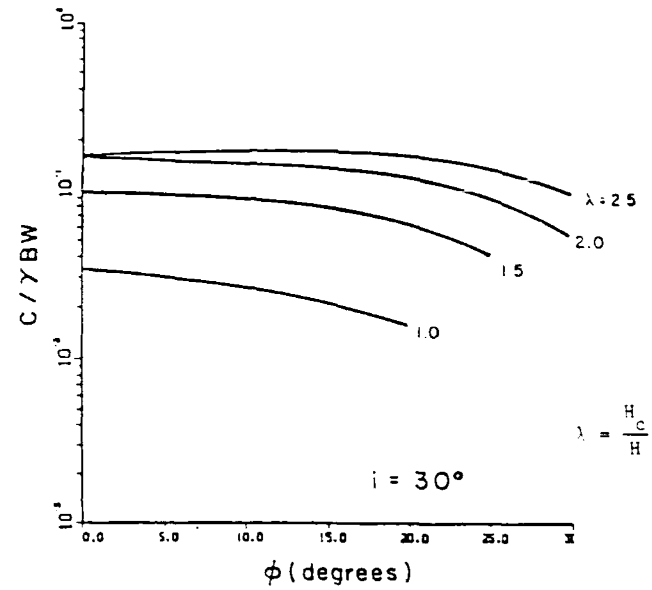

Figure 3.16. Estimation of failure block width (gentle slope).

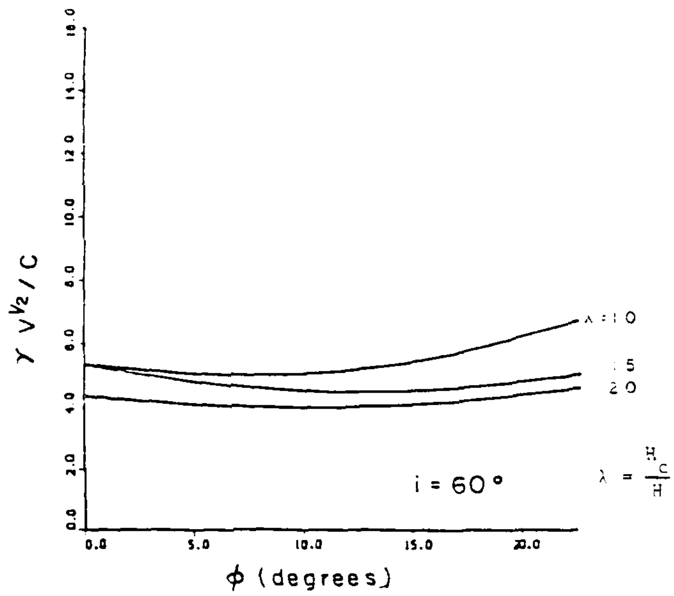

Figure 3.17. Estimation of failure block volume (gentle slope).

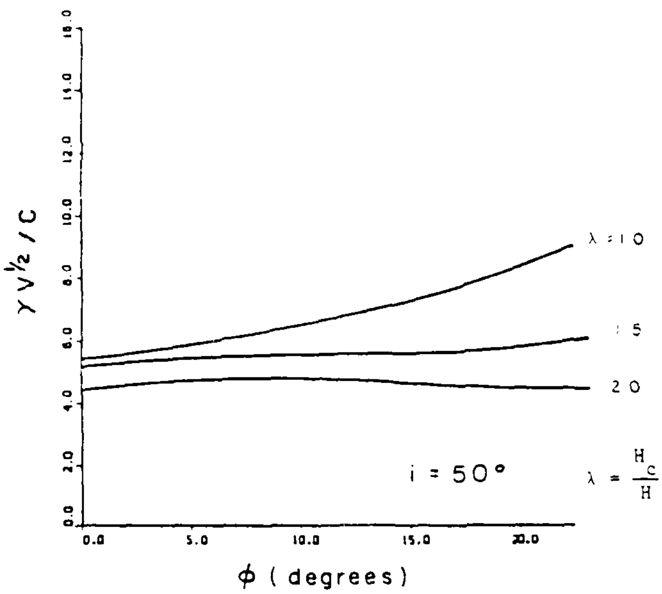

Figure 3.18. Estimation of failure block volume (gentle slope).

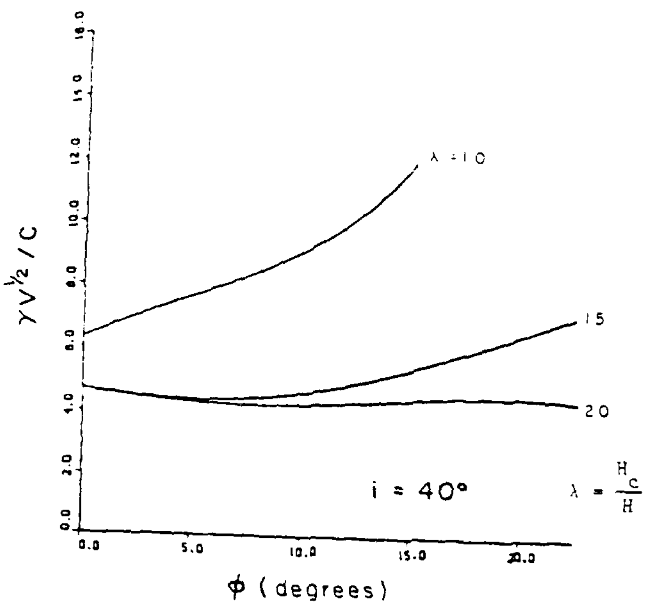

Figure 3.19. Estimation of failure block volume (gentle slope).

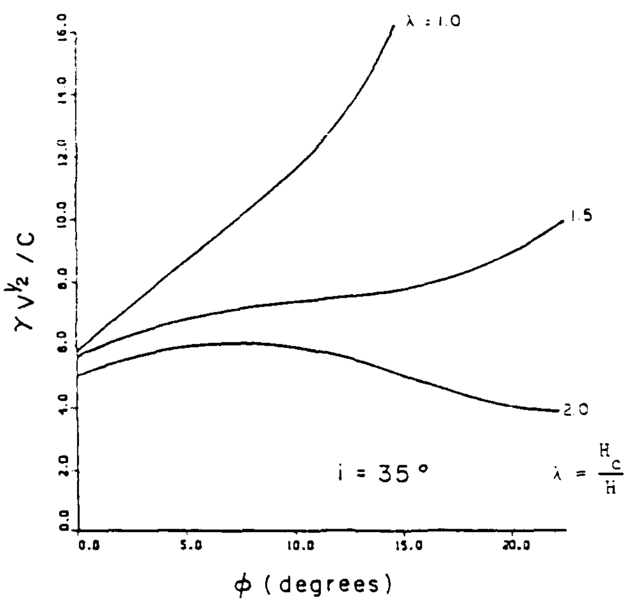

Figure 3.20. Estimation of failure block volume (gentle slope).